

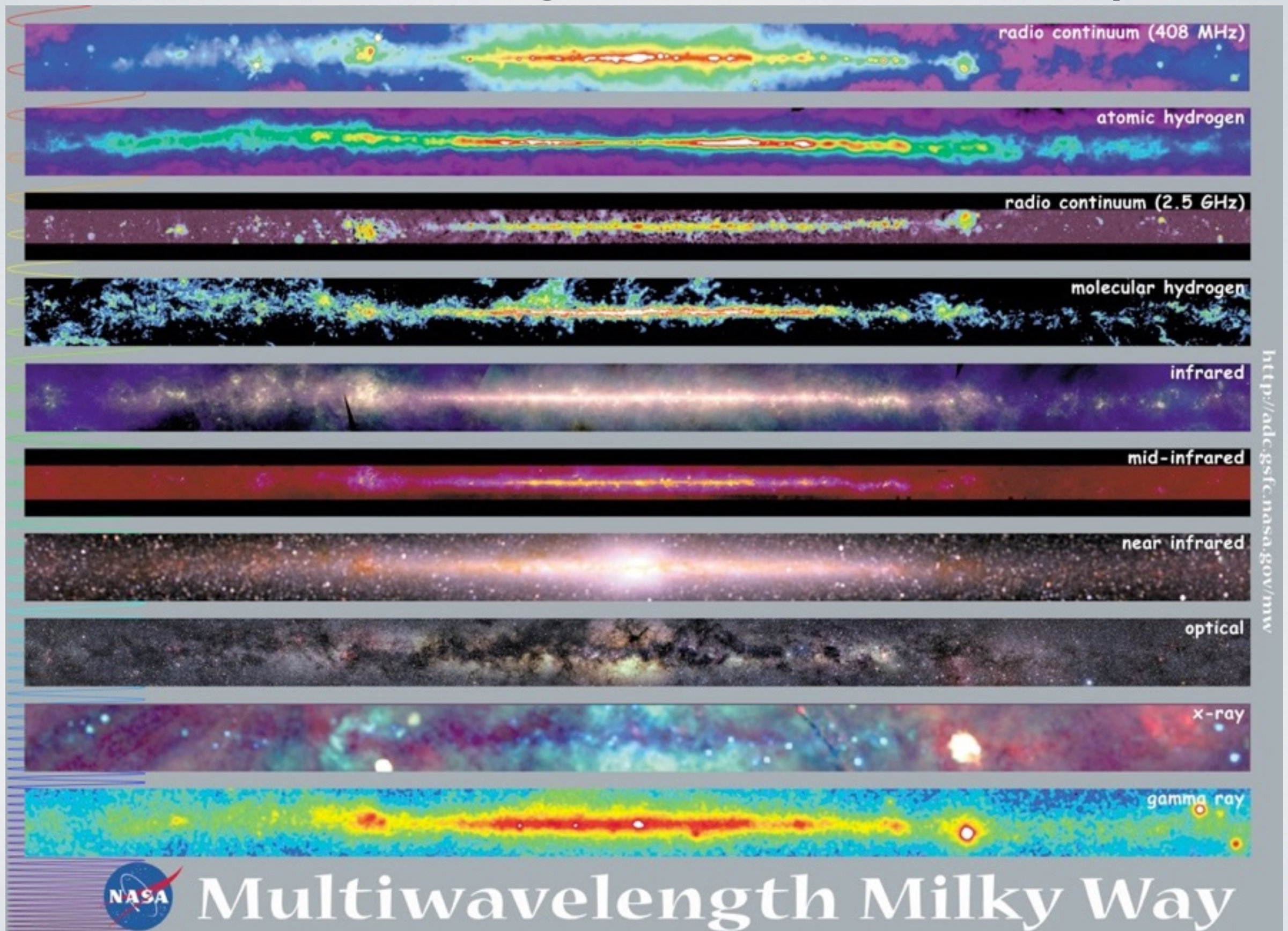
# Gamma-ray Survey of our Universe



C. Michelle Hui  
NASA/MSFC  
Oct 12, 2016



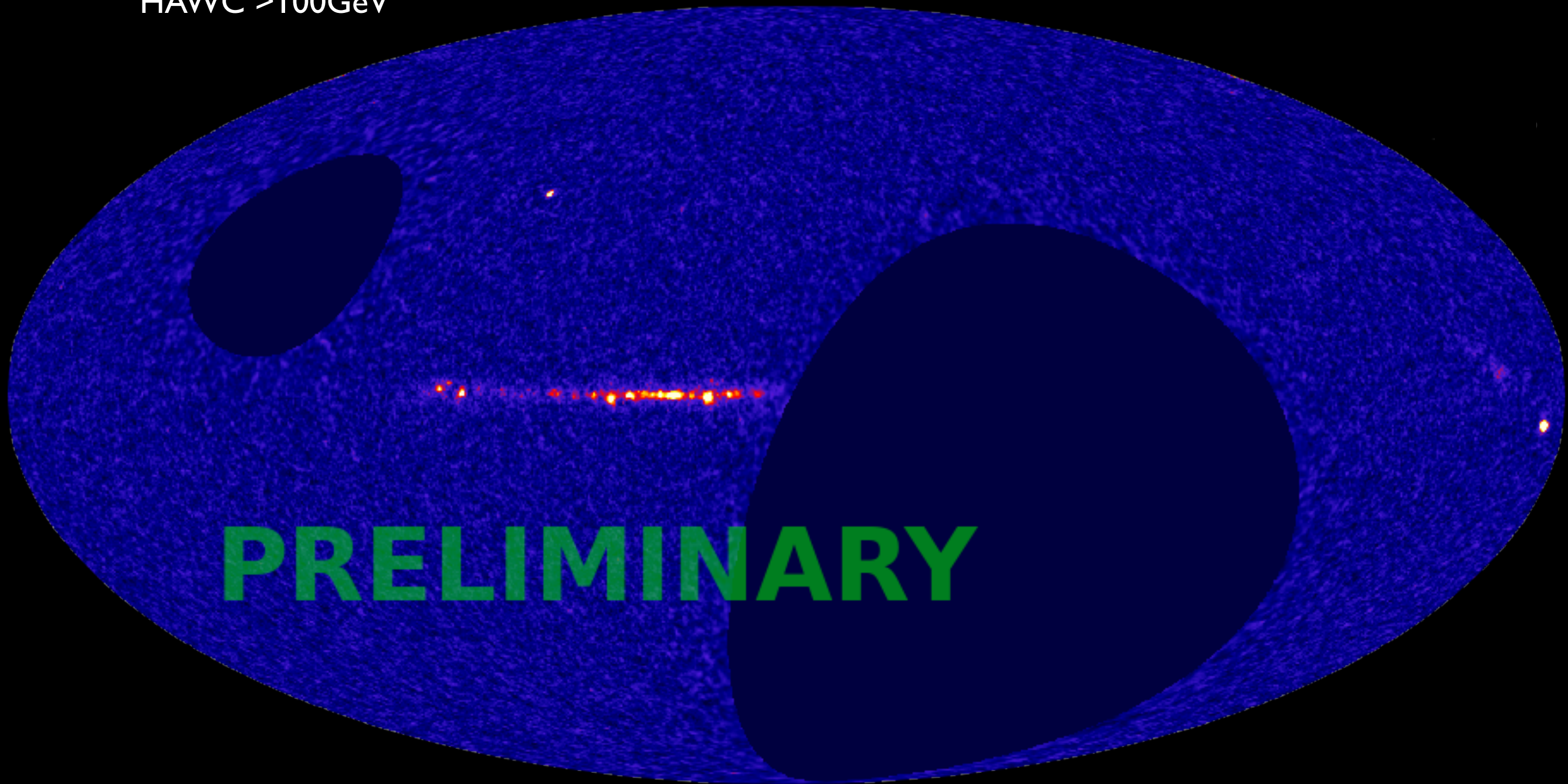
# Multi-Wavelength View of our Galaxy





# Gamma-ray View of our Galaxy

HAWC >100GeV

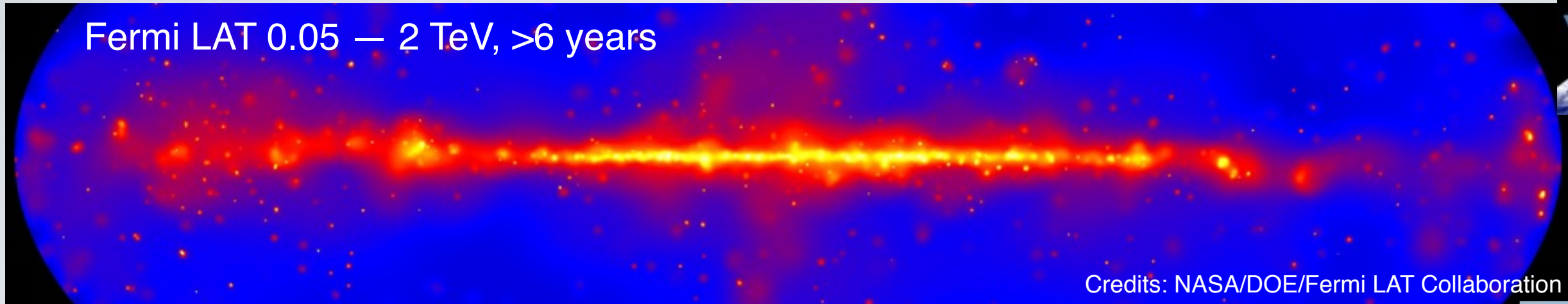


Credits: NASA/DOE/Fermi LAT Collaboration



# High Energy View of our Galaxy

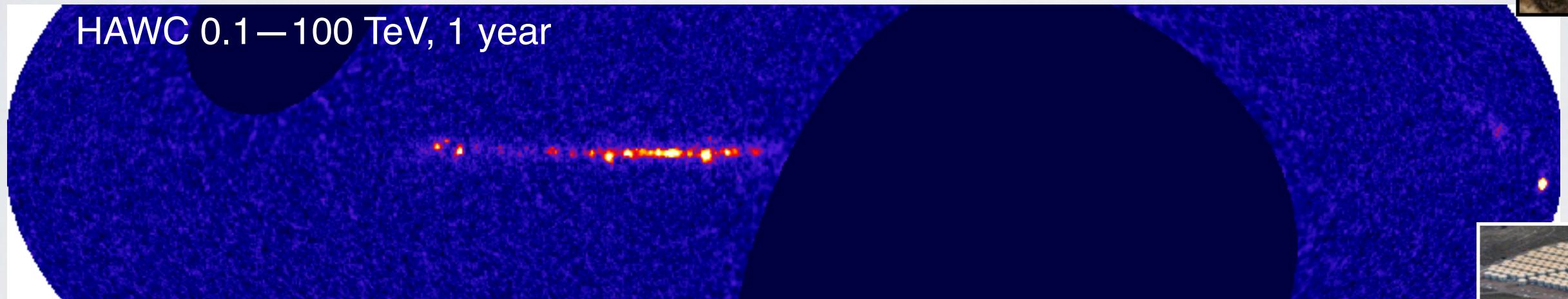
Fermi LAT 0.05 — 2 TeV, >6 years



HESS >1TeV, 10 years



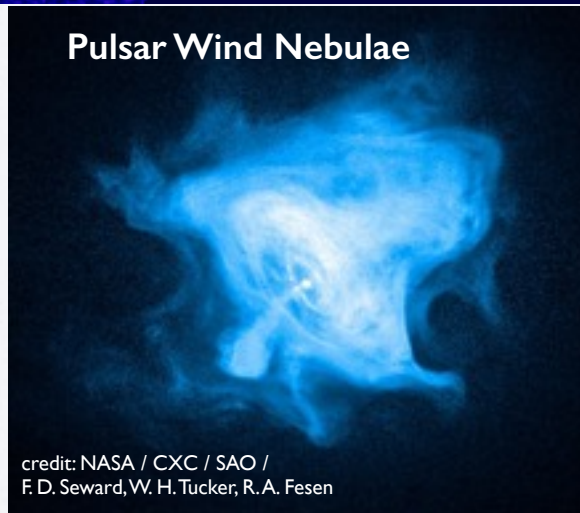
HAWC 0.1 — 100 TeV, 1 year



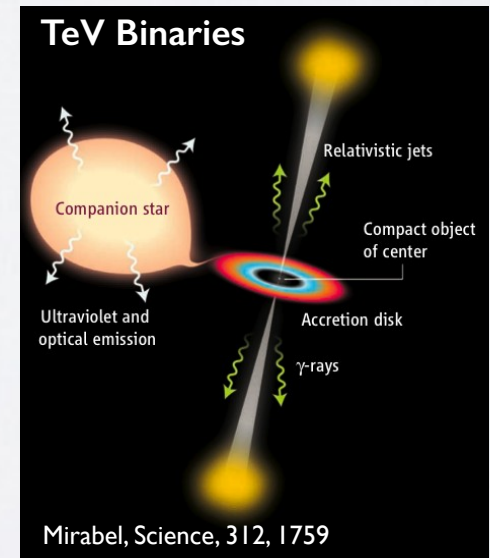
Supernova Remnants



Pulsar Wind Nebulae



TeV Binaries





# Gamma-Ray Detectors

Wide Field of View, Continuous Operations

FACT



MAGIC



Sensitivity



Milagro  
2000-2008

Tibet AS- $\gamma$   
1990-present



VERITAS



HAWC  
2013 - present

ARGO  
2007-2014



HESS



MAGIC  
VERITAS



# HAWC collaboration



Georgia Institute of Technology  
George Mason University  
Los Alamos National Laboratory  
Michigan State University  
Michigan Technological University  
NASA/Goddard Space Flight Center  
NASA/Marshall Space Flight Center  
Pennsylvania State University  
Stanford University  
University of California, Irvine  
University of California, Santa Cruz  
University of Maryland  
University of New Hampshire  
University of New Mexico  
University of Rochester  
University of Wisconsin-Madison  
University of Utah

Centro de Investigacion en Computacion, IPN  
Centro de Investigacion y de Estudios Avanzados del IPN  
Benemérita Universidad Autónoma de Puebla  
Universidad Nacional Autónoma de México:  
Instituto de Astronomía  
Instituto de Ciencias Nucleares  
Instituto de Física  
Instituto de Geofísica  
Instituto Nacional de Astrofísica, Óptica y Electrónica  
Universidad Autónoma del Estado de Hidalgo  
Universidad Michoacana de San Nicolás de Hidalgo  
Universidad Autónoma de Chiapas  
Universidad Politecnica de Pachuca  
Universidad de Guadalajara  
Max-Planck Institute for Nuclear Physics  
Instytut Fizyki Jadrowej im Henryka Niewodniczanskiego  
Polskiej Akademii Nauk

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Red de Física de Altas Energías, México;  
DGAPA-UNAM, México;  
and the University of Wisconsin Alumni Research Foundation.



## HAWC Observatory

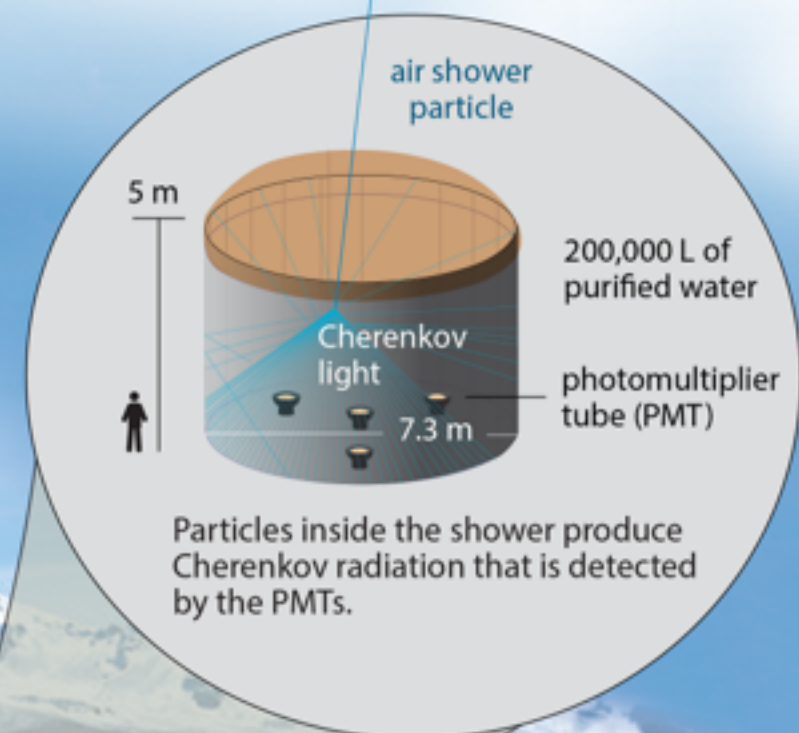
HAWC operates day and night, providing a large field of view for the observation of the highest energy gamma rays.



Pico de Orizaba  
(5,626 m)

## Water Cherenkov tank

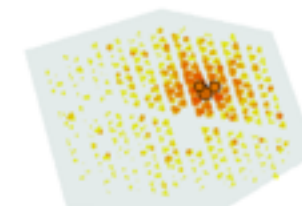
HAWC comprises an array of 300 tanks that record the particles created in gamma-ray and cosmic-ray showers.



## Gamma rays vs cosmic rays

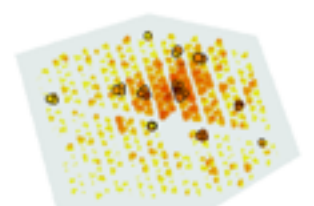
HAWC selects gamma rays from among a much more abundant background of cosmic rays.

gamma-ray shower



"hot" spots concentrate around the core

cosmic-ray shower



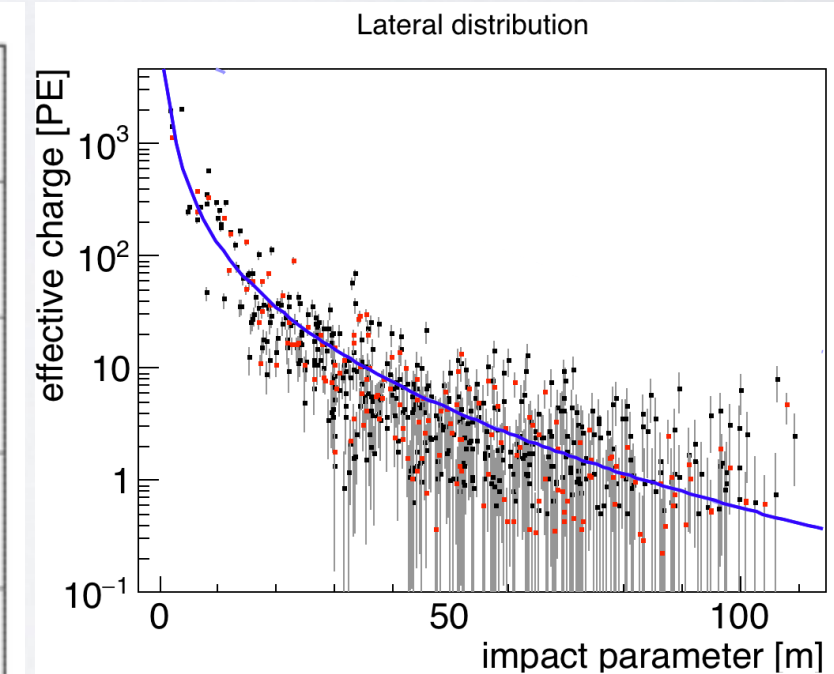
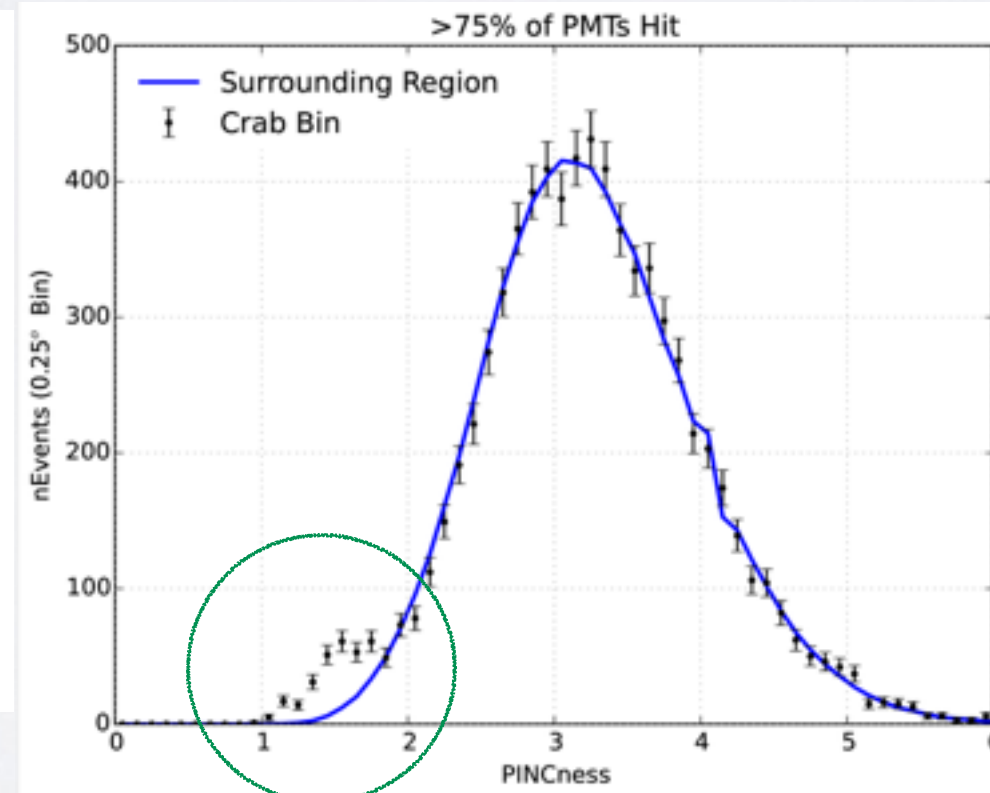
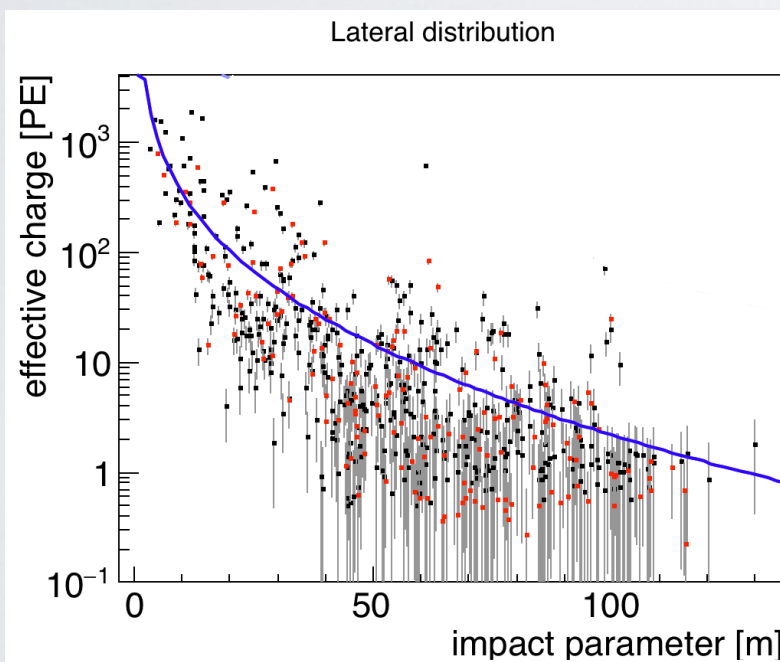
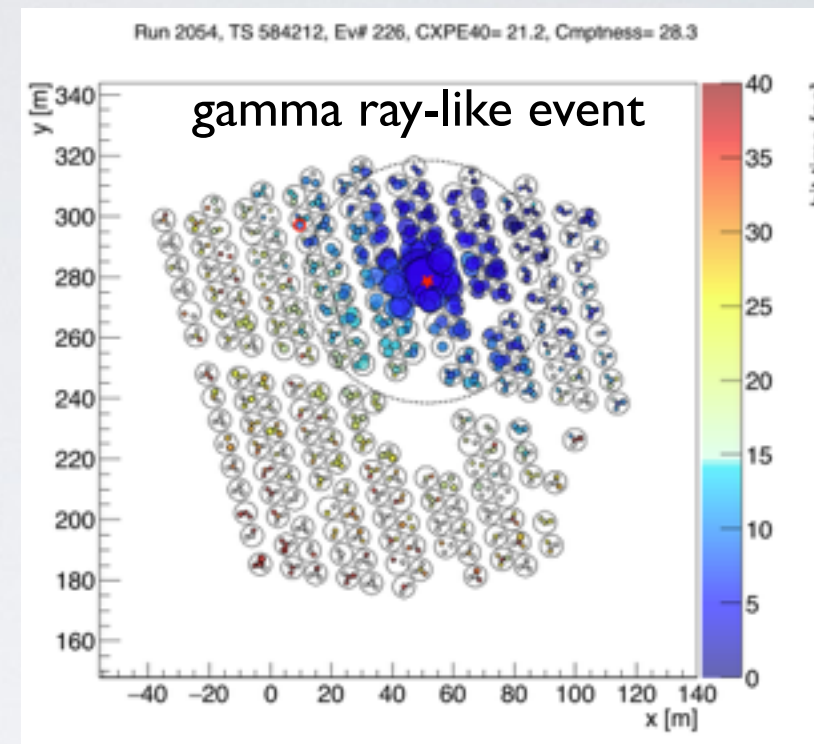
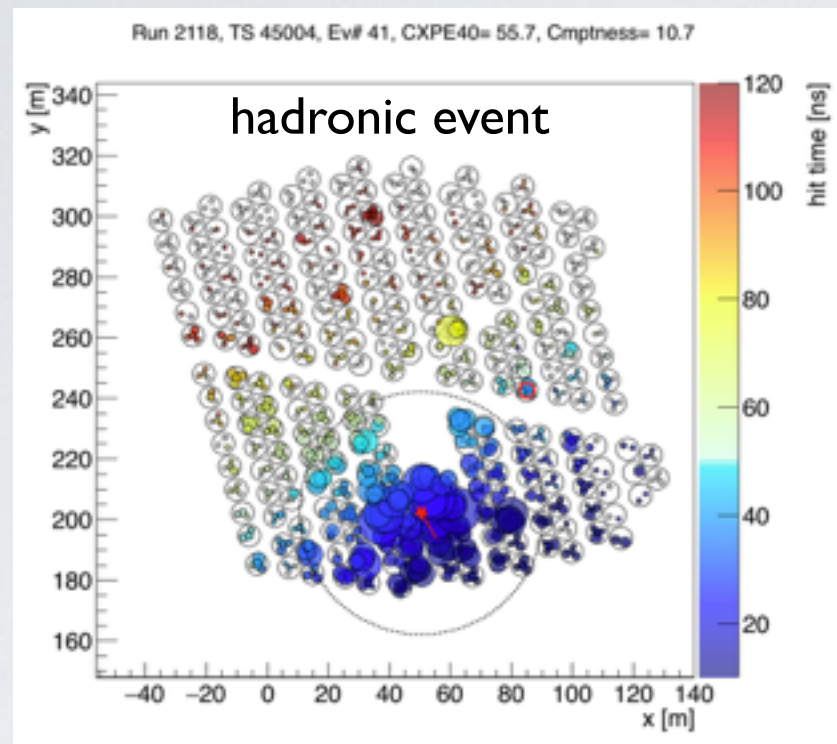
"hot" spots are more dispersed

HAWC is located at 4,100 m above sea level, covering an area of 20,000 m<sup>2</sup>.

150 m

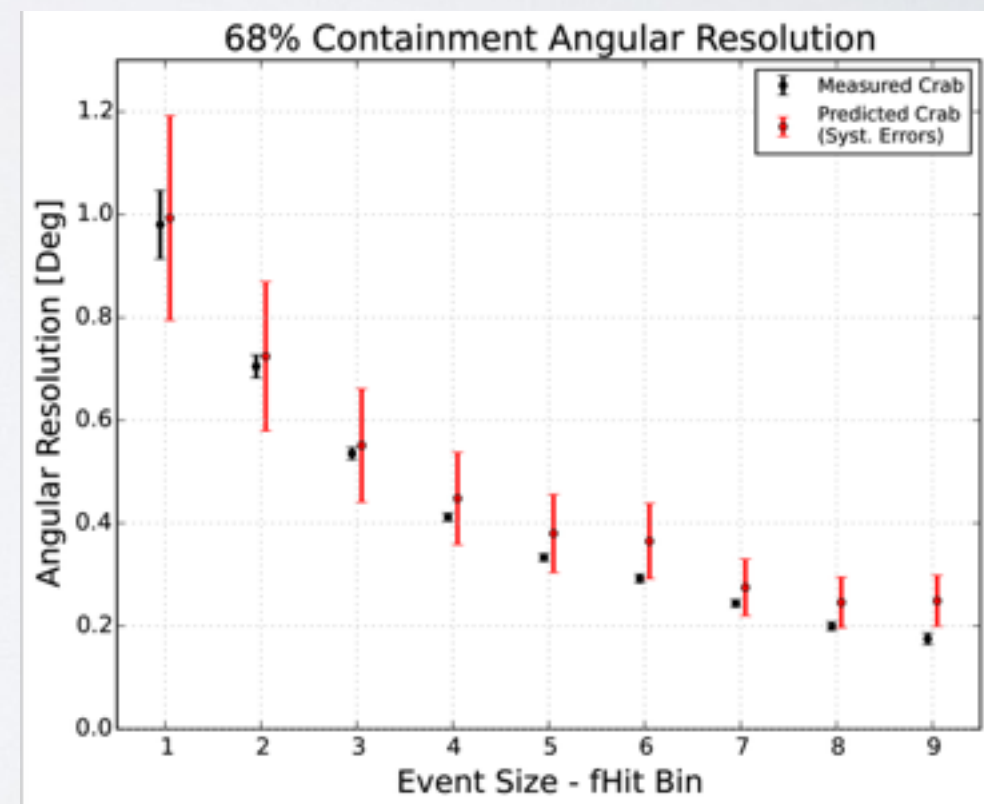
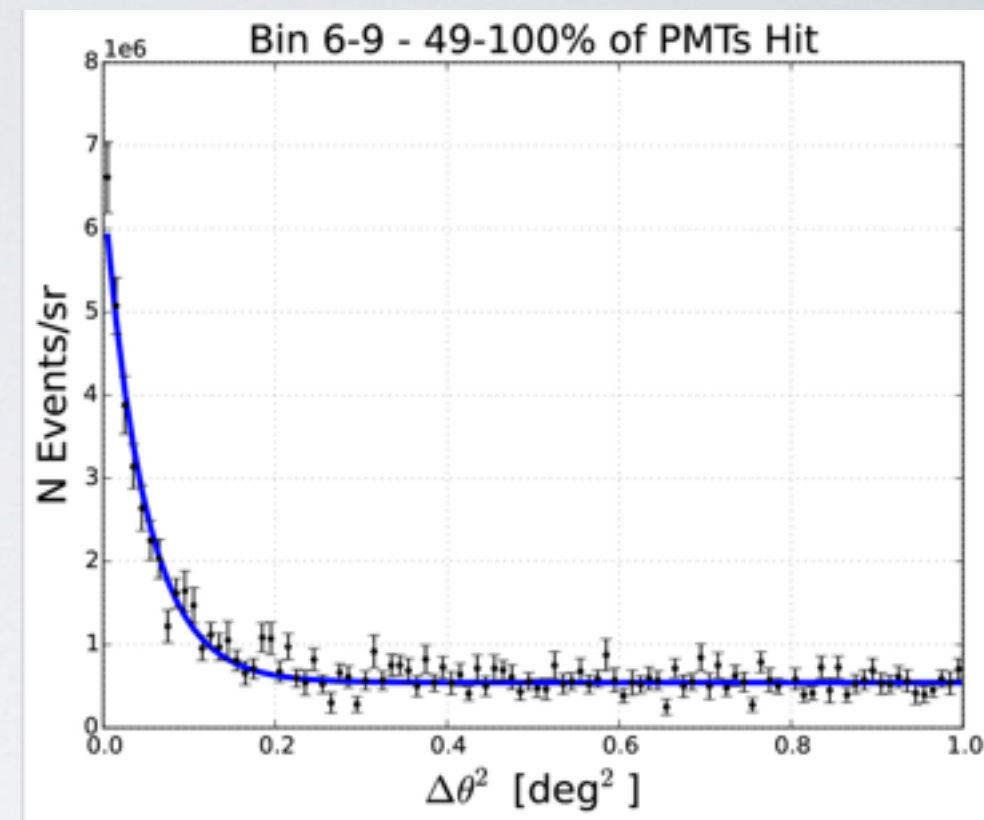
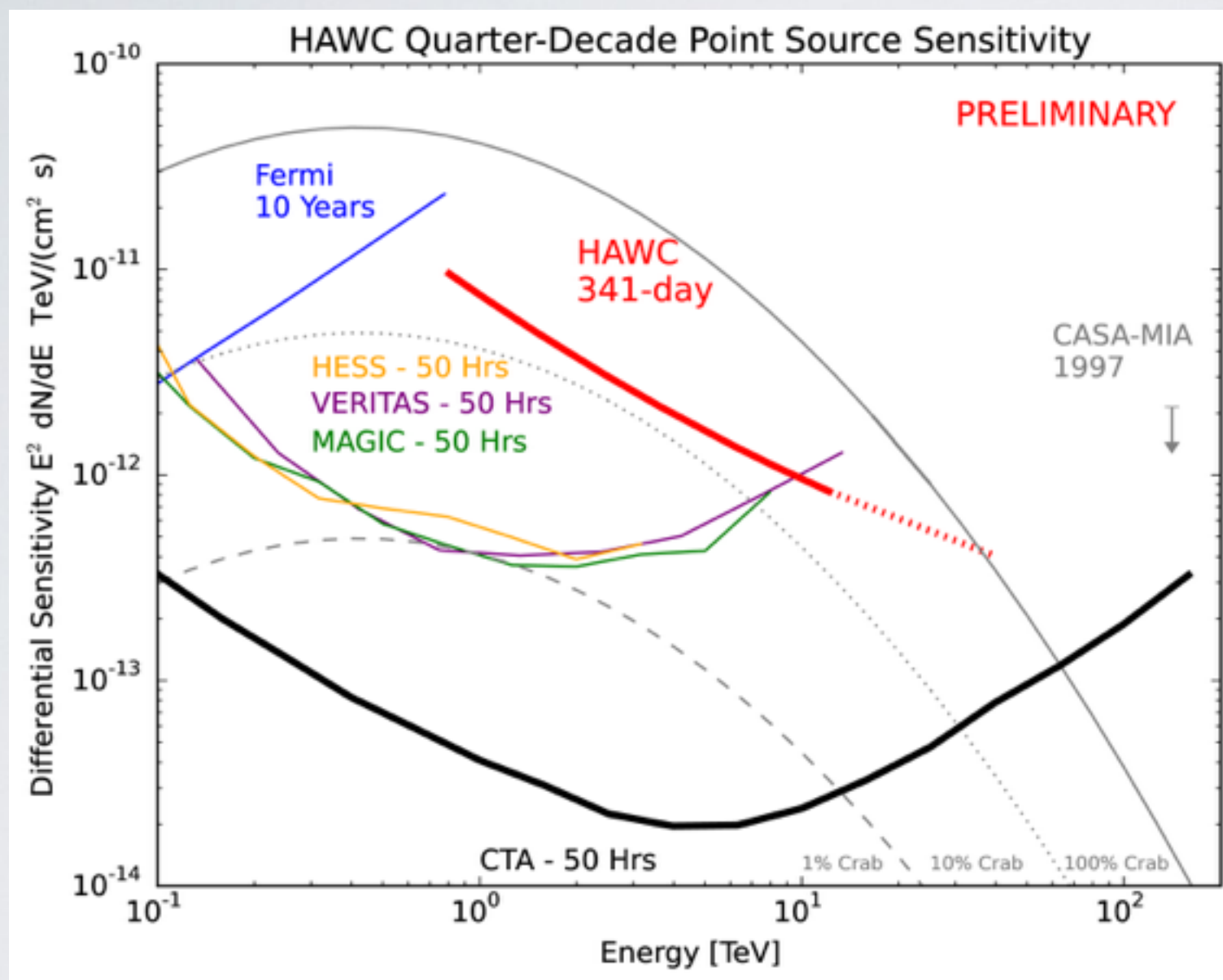


# Gamma/Hadron Separation





# HAWC Sensitivity



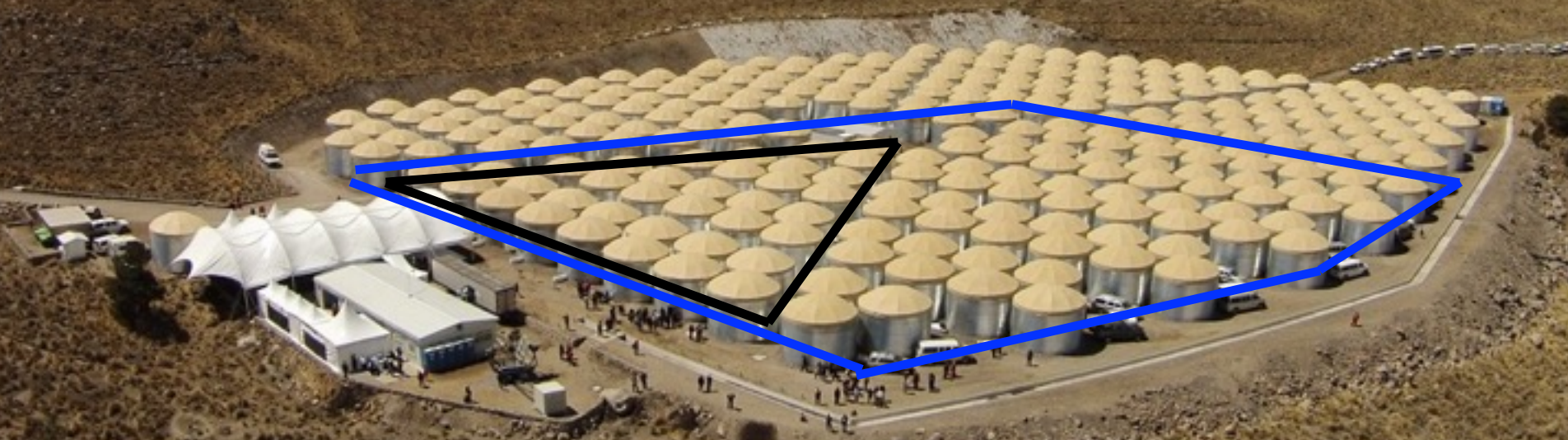
- $0.2^\circ$  PSF<sub>68%</sub> at highest energy





# High Altitude Water Cherenkov Gamma-ray Observatory

- Sensitive from 100 GeV to 100 TeV.
- Angular resolution (68% containment) 0.2-1.0 degrees.
- 2sr instantaneous field of view, 2/3 of sky each day.
- >95% duty cycle.
- **Strengths:**
  - Extreme high-energy reach.**
  - Wide field-of-view: ideal for transients and extended objects.**
  - High duty cycle.**

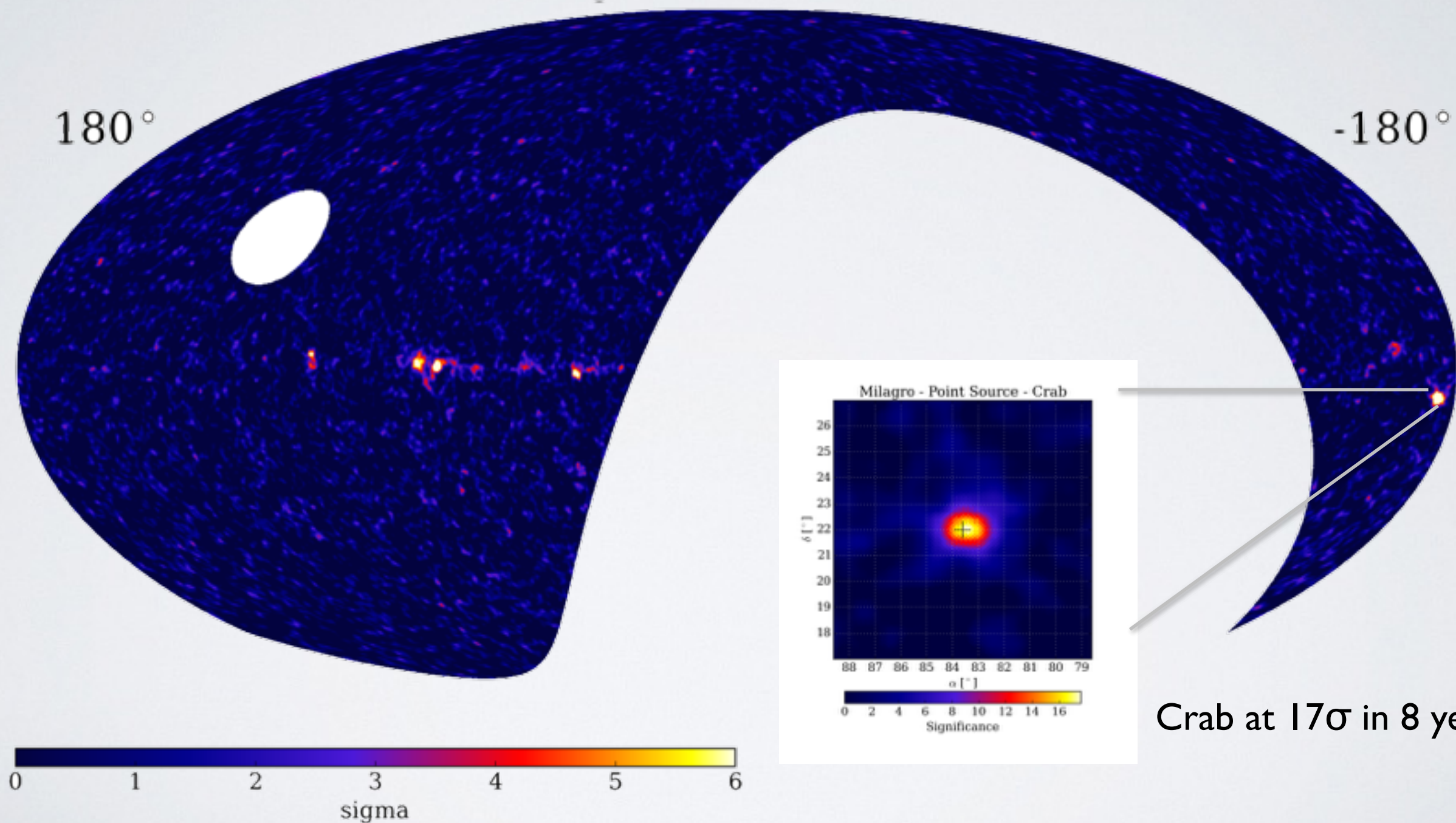


HAWC-30: began Aug 2012  
HAWC-III: Jun 2013 (~280 days)  
HAWC: Nov 2014 (341+ days)  
Inauguration Mar 2015



# Milagro 8-Year TeV Sky Survey

HAWC predecessor

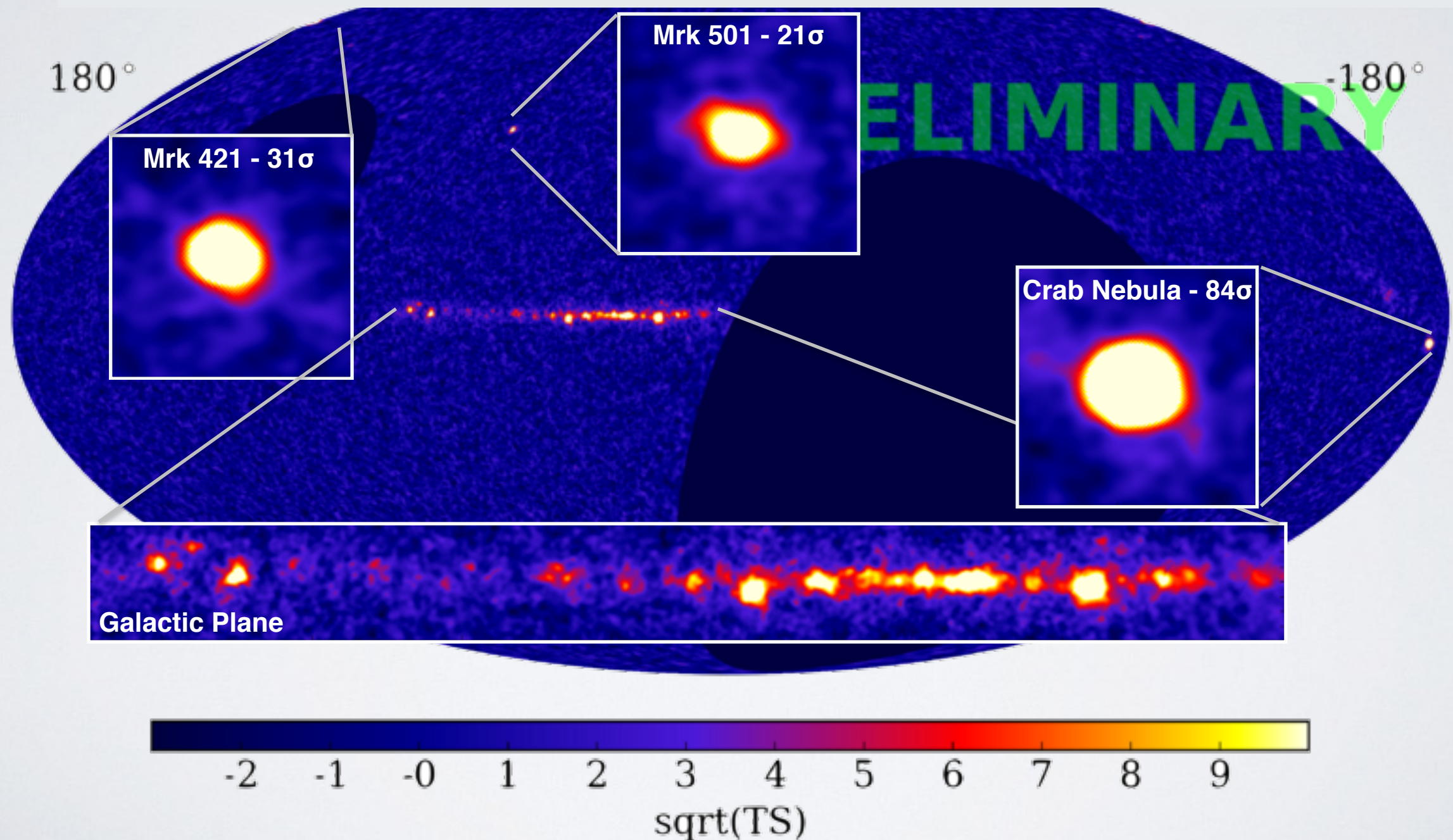


Crab at  $17\sigma$  in 8 years.



# HAWC TeV Sky Survey

- HAWC is  $\sim 15\times$  more sensitivity with lower energy threshold compared to Milagro, and more sensitive towards Galactic center.
- Skymap from 341 days of data taken with the finished HAWC array.
- Point source analysis assuming power-law index of 2.7.

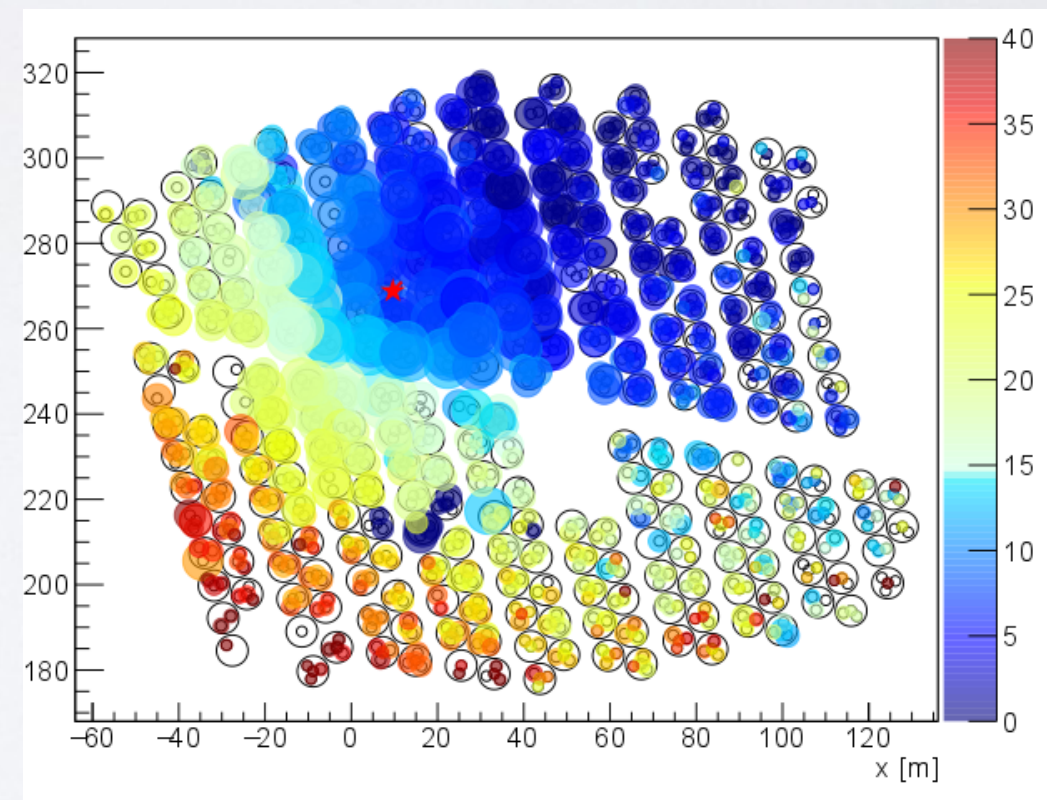
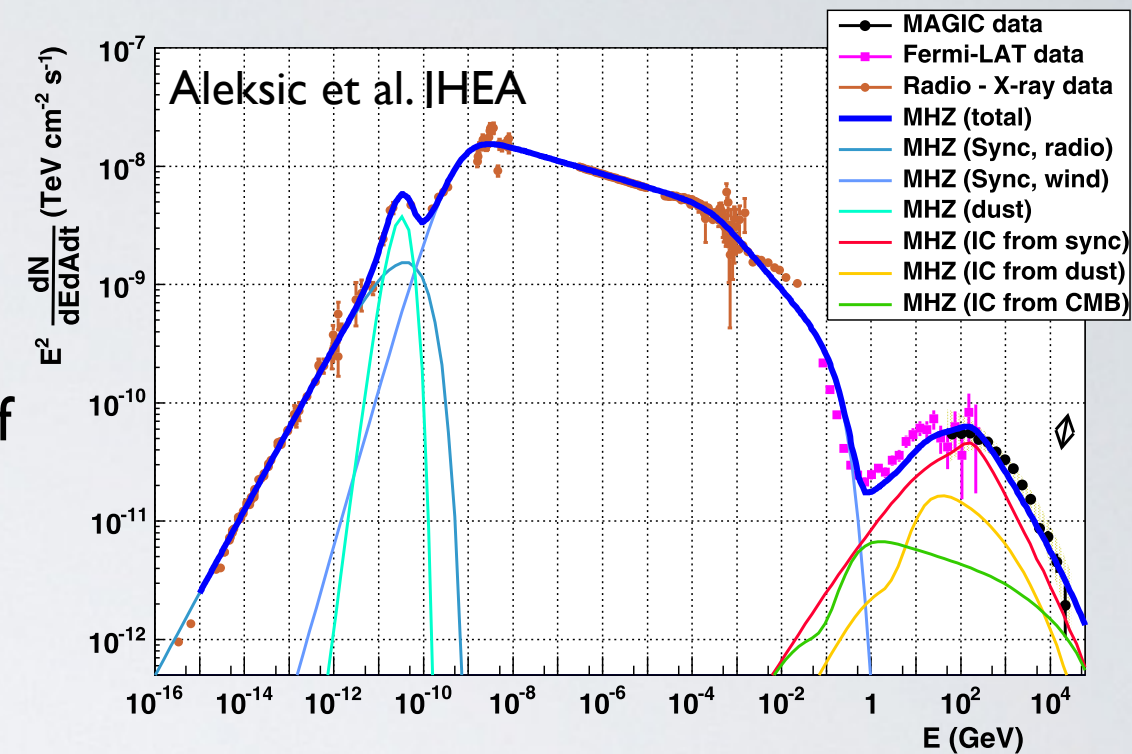
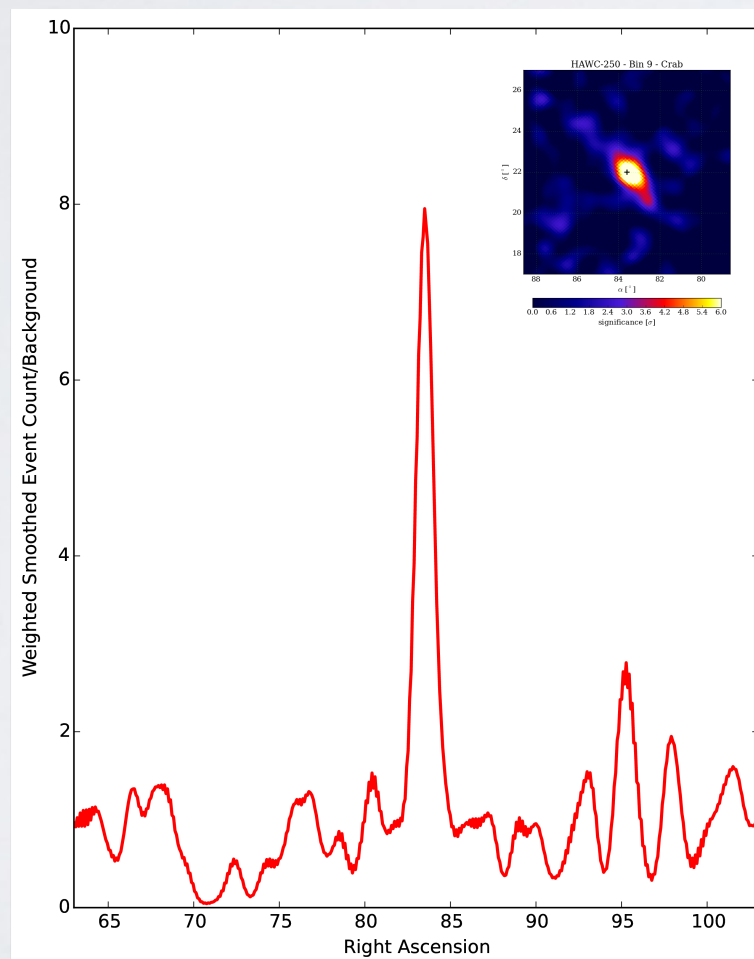




# Pulsar Wind Nebulae

## Crab Nebula at highest energies

- photons up to 80TeV reported by IACTs
- insight into magnetic field environment and efficiency of particle acceleration



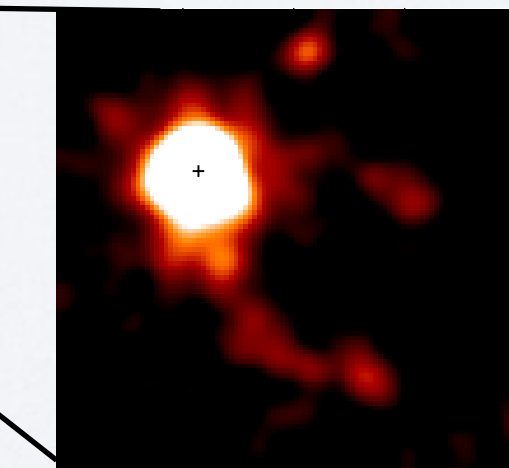
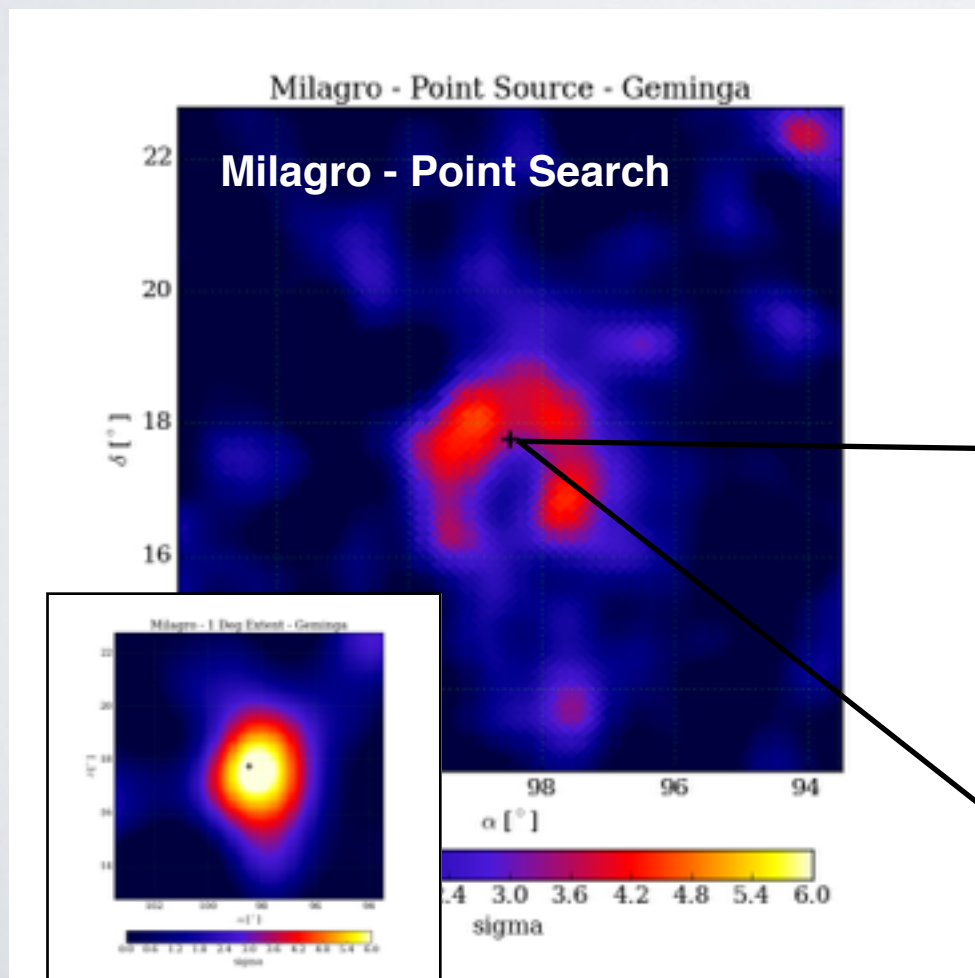
60TeV photon from the Crab Nebula seen by HAWC.



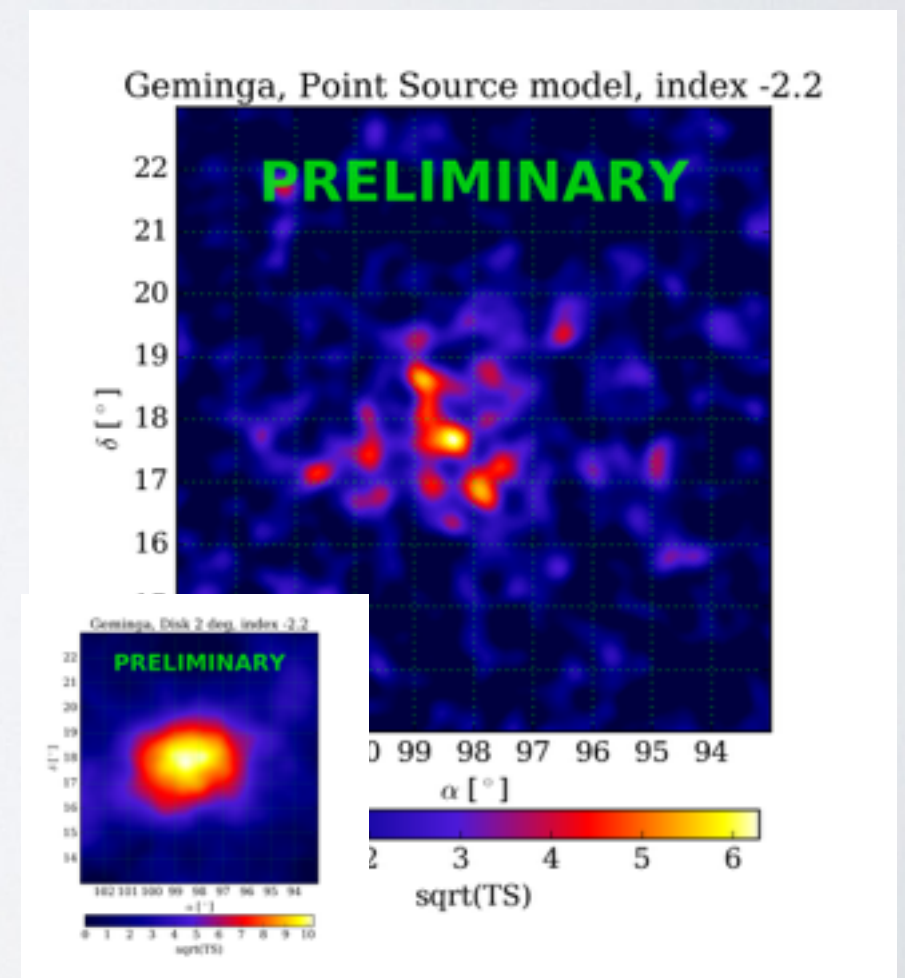
# Pulsar Wind Nebulae

## Geminga

- Closest known middle aged pulsar
- Possible nearby cosmic ray acceleration site  
— explanation for positron excess (Yuksel et al. 2009)
- Not seen by IACTs, extent maybe larger than IACT FOV.
- Ongoing morphological and spectral studies



XMM, Pavlov et al. 2010





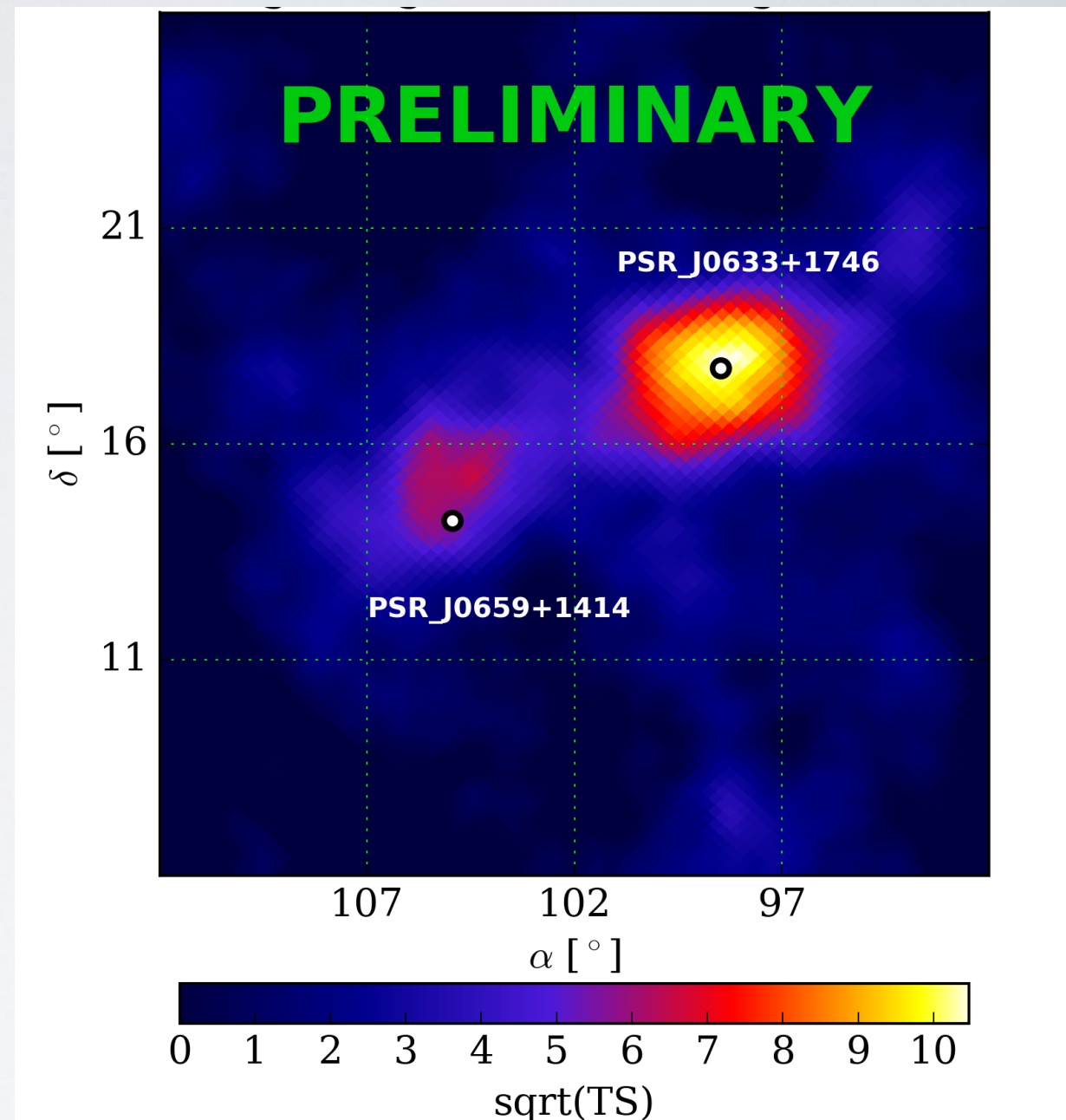
# Pulsar Wind Nebulae

## PSR J0659+14

- New PWN seen near Geminga!
- Similar large extension seen in data.
- This pulsar is very similar to Geminga pulsar:

	Geminga	PSR J0659+14
age [yr]	3E+05	1E+05
distance [pc]	250	288
spin-down power [erg/s]	3E+34	4E+34

- Geometry and diffusion studies on propagation of electron/positron to Earth.





# New TeV Sources!

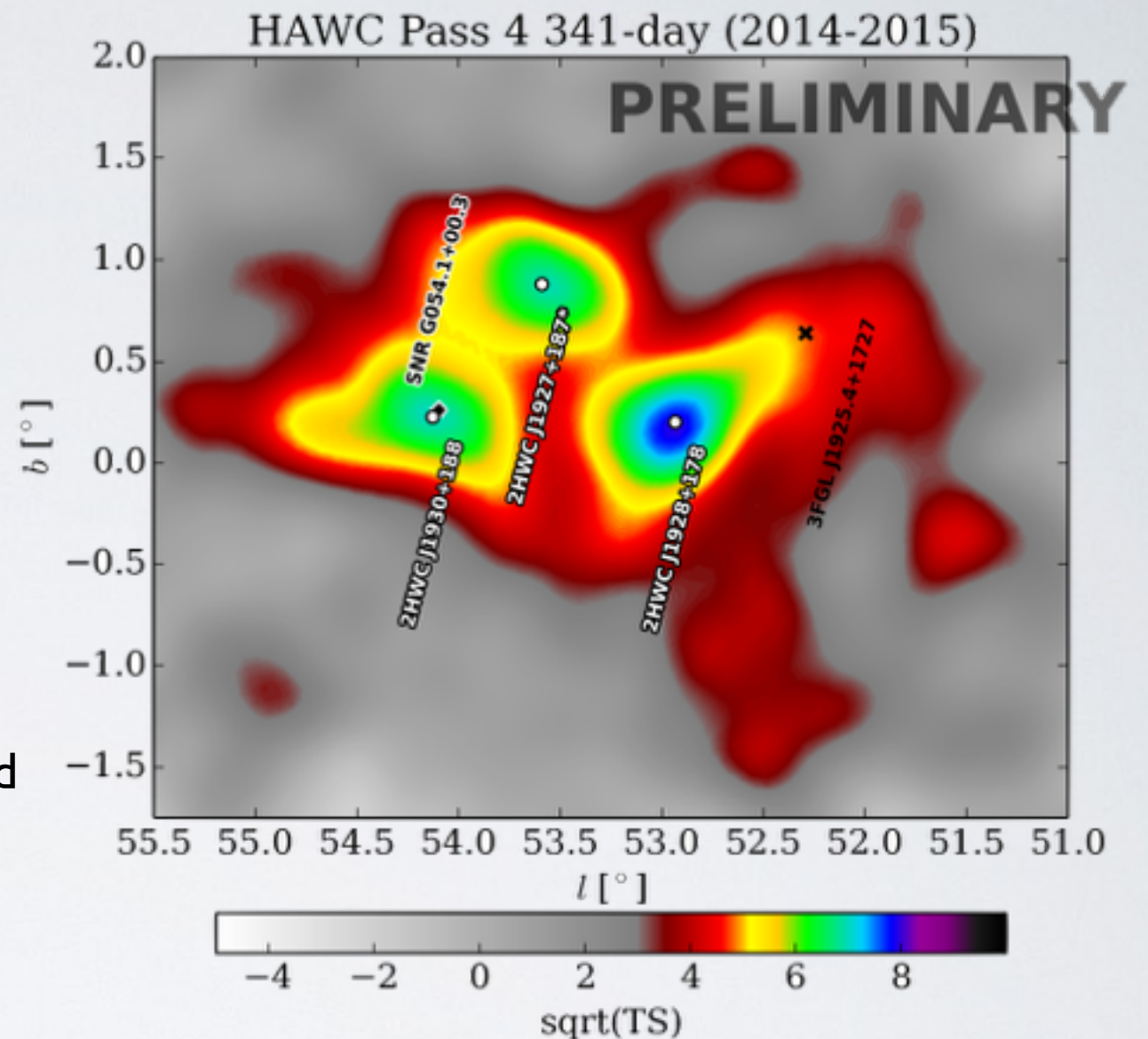
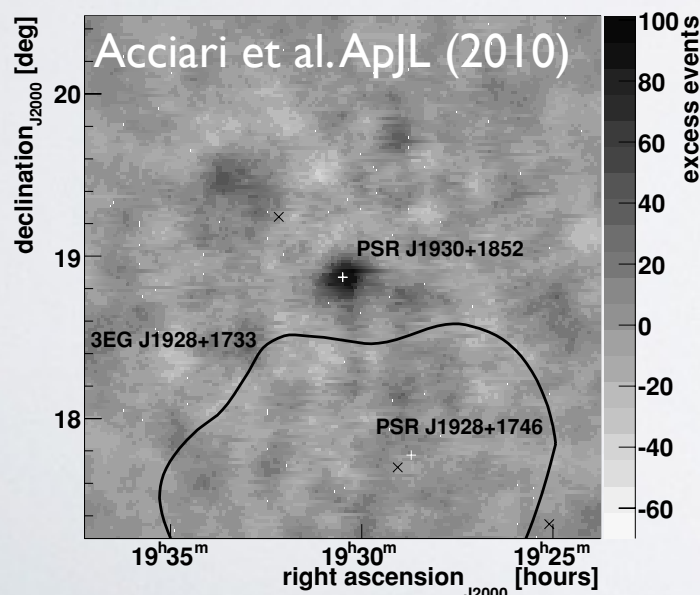
## New TeV emission region

2HWC J1927+187\*

- $\sim 7\sigma$  pre-trials
- current blind search algorithm identify this region associated with 2HWC J1930+188, ongoing analysis on spatial morphology

2HWC J1930+188

- coincident with VER J1930+188 (SNR G54.1+00.3 / PSR J1930+1852)
- TeV emission was reported to be point-like and likely from PWN
- nearby molecular CO cloud



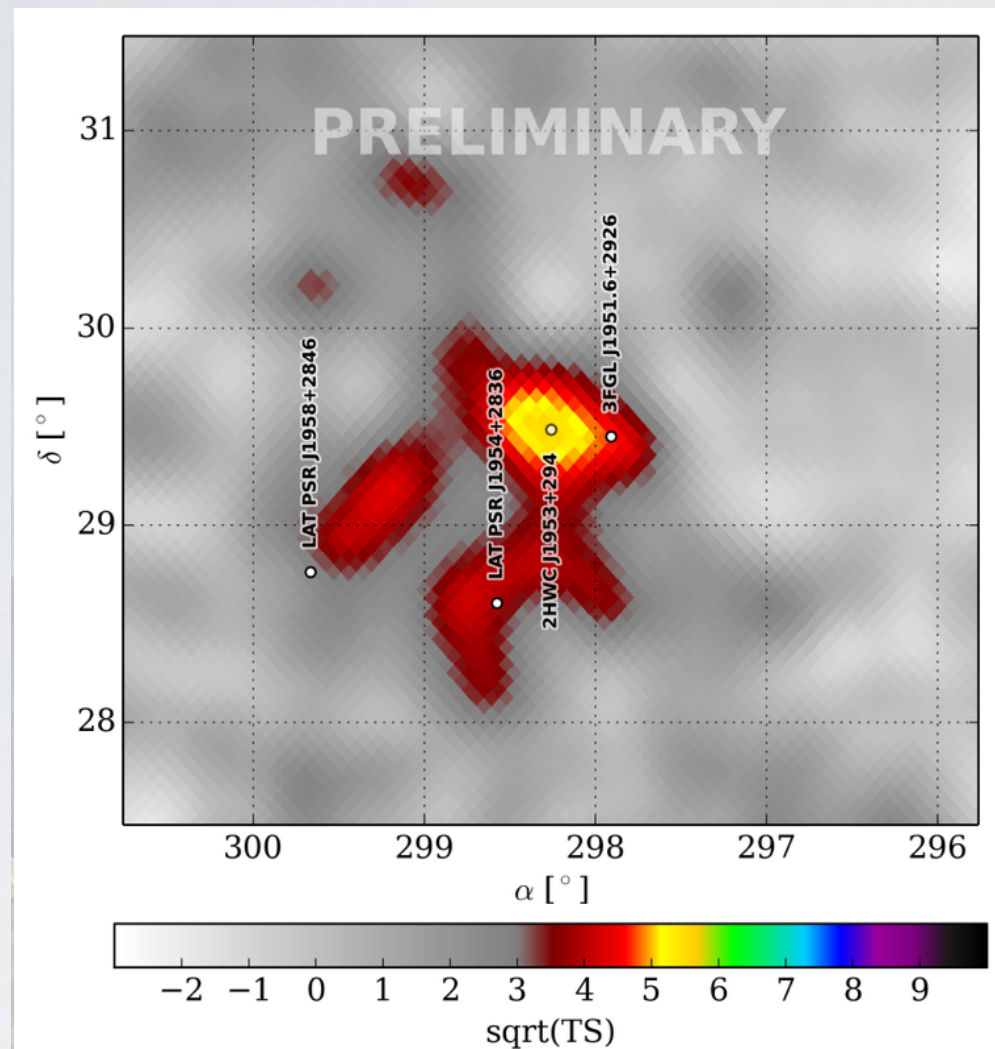
## New TeV source

2HWC J1928+178

- $\sim 8\sigma$  pre-trials
- coincident with PSR J1928+1746
- tail towards unidentified source 3FGL J1925.4+1727
- VERITAS point source upper limit  $\sim 1.4\%$  of Crab



# New TeV Sources!

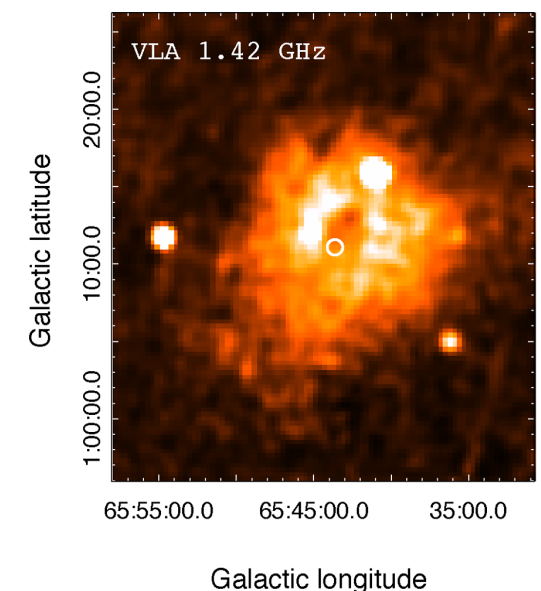
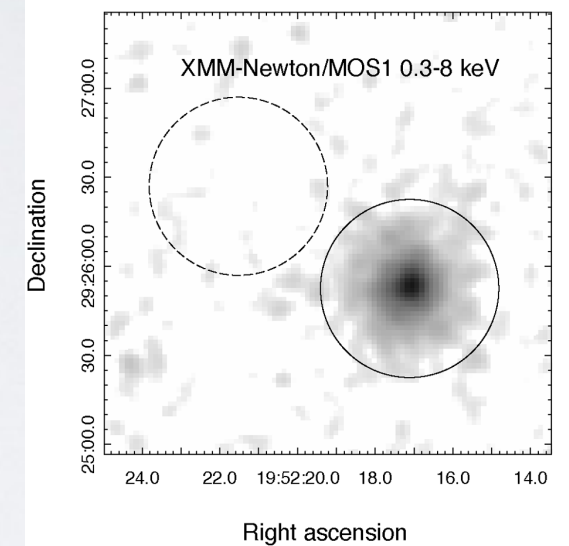
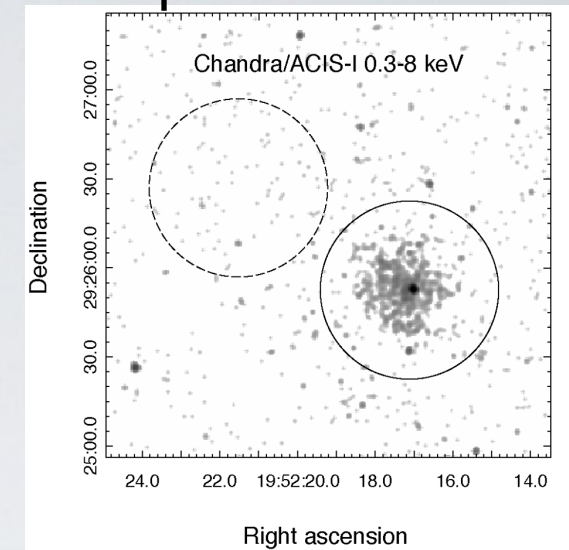


## New TeV source

2HWC J1953+294

- confirmed by VERITAS
- potential association:
  - PWN DA 495 seen in X-rays
  - 3FGL J1951.6+2926

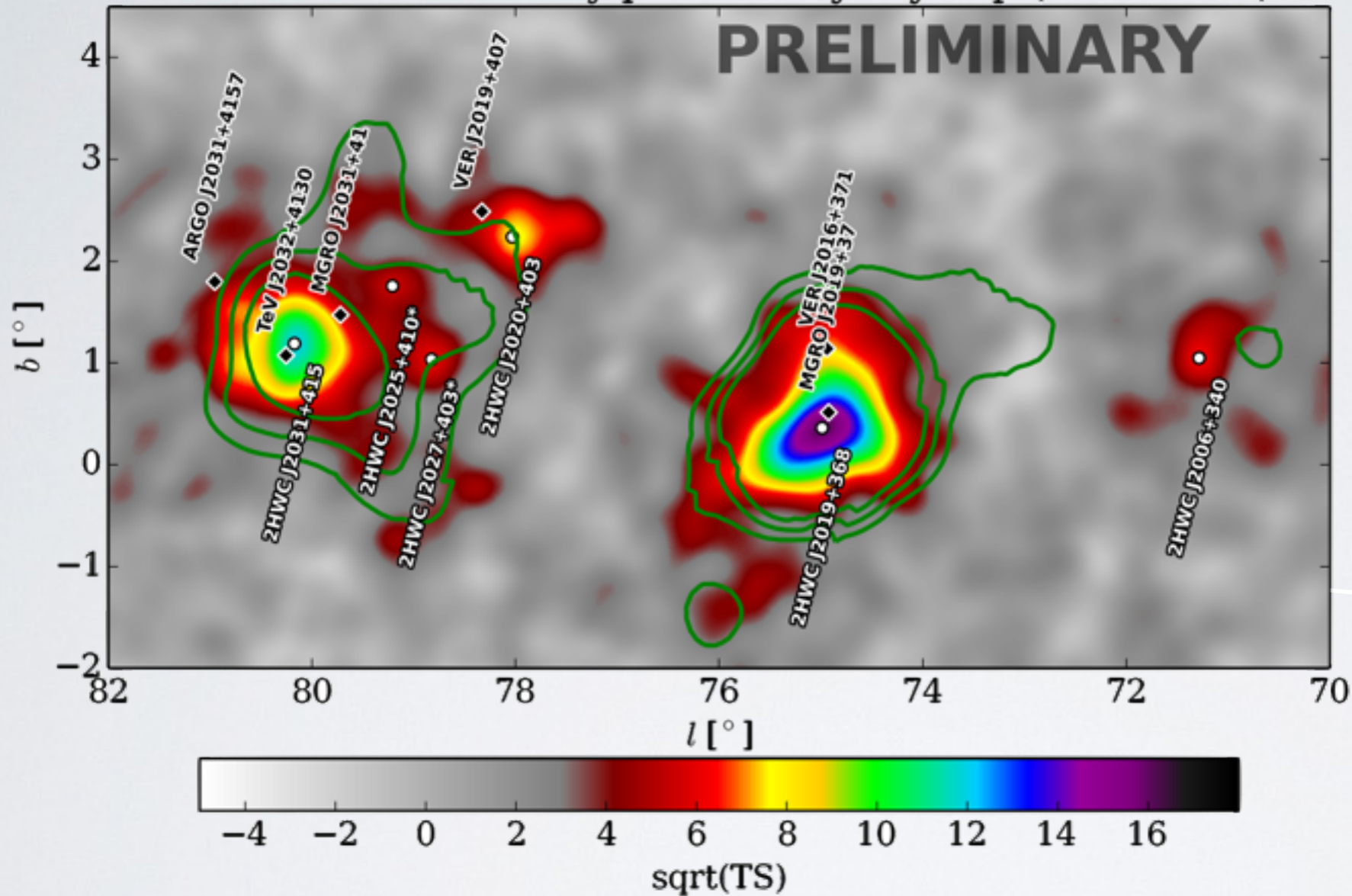
Karpova et al 2015





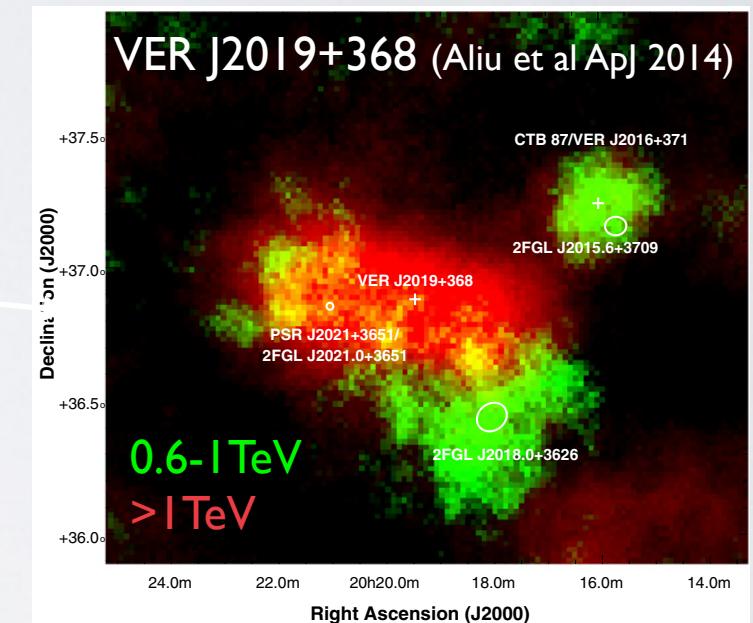
# Cygnus Region

HAWC Pass 4 341-day preliminary skymap (2014-2015)



New TeV source  
2HWCJ2006+340:

- $>6\sigma$  pre-trials
- $0.6^\circ$  from unidentified source 3FGL J2004.4+3338

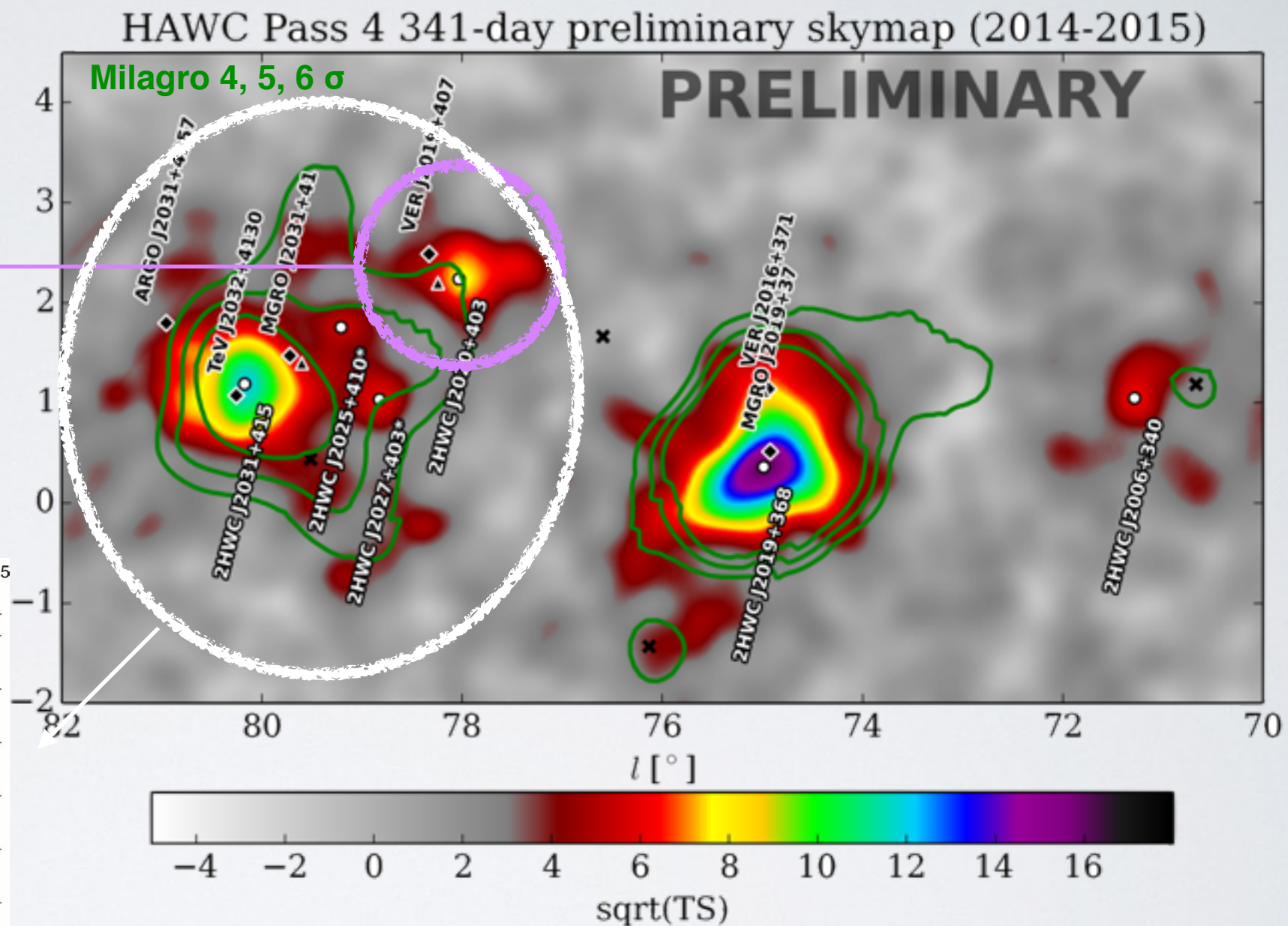
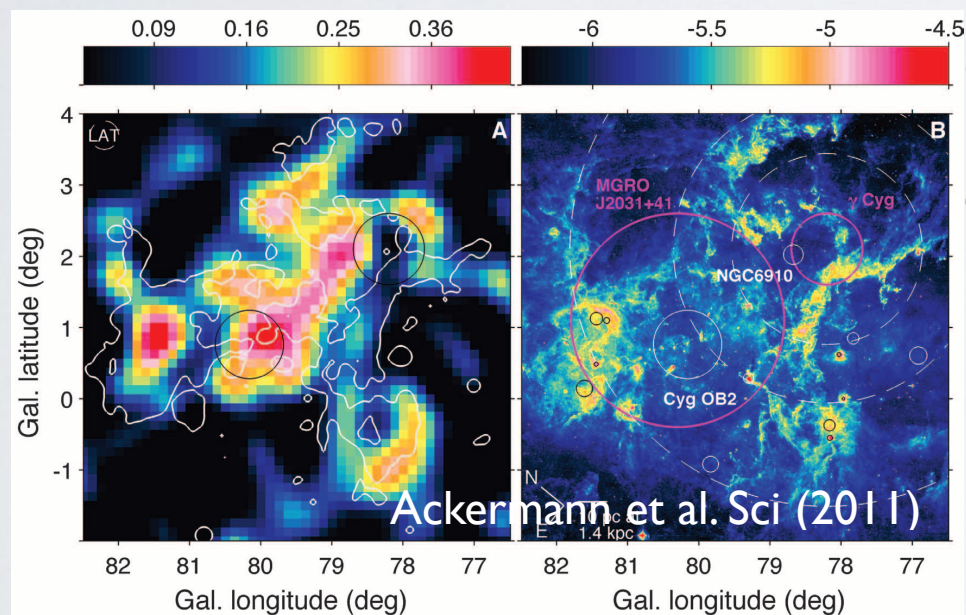
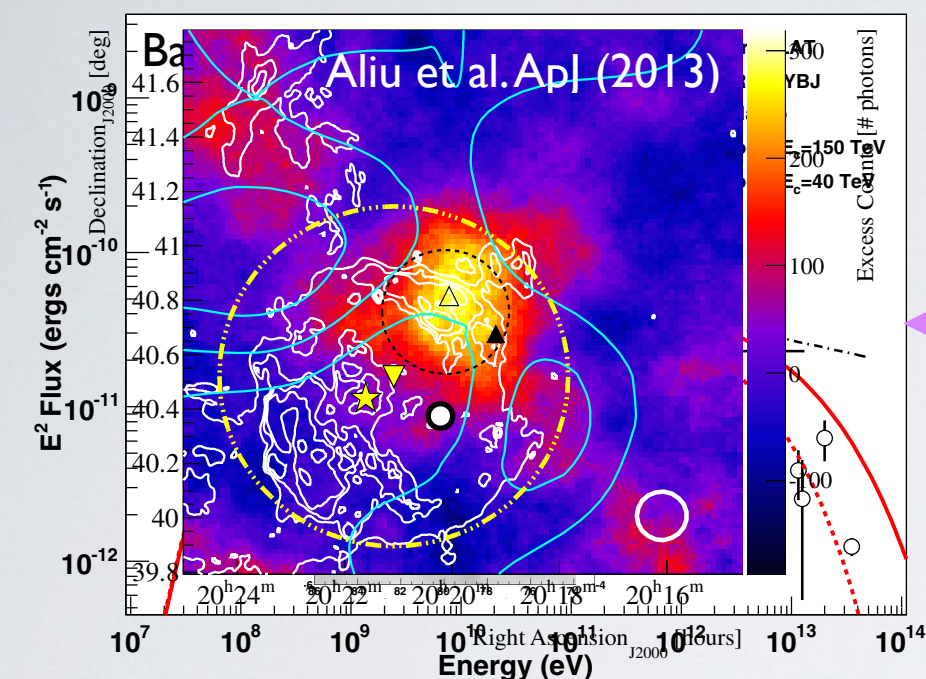


2HWC J2019+368 is coincident with MGRO J2019+37 and VER J2019+368

- extended emission including PSR J2021+3651 and HII region Sh 2-104



# Cygnus Region



two distinct TeV sources:

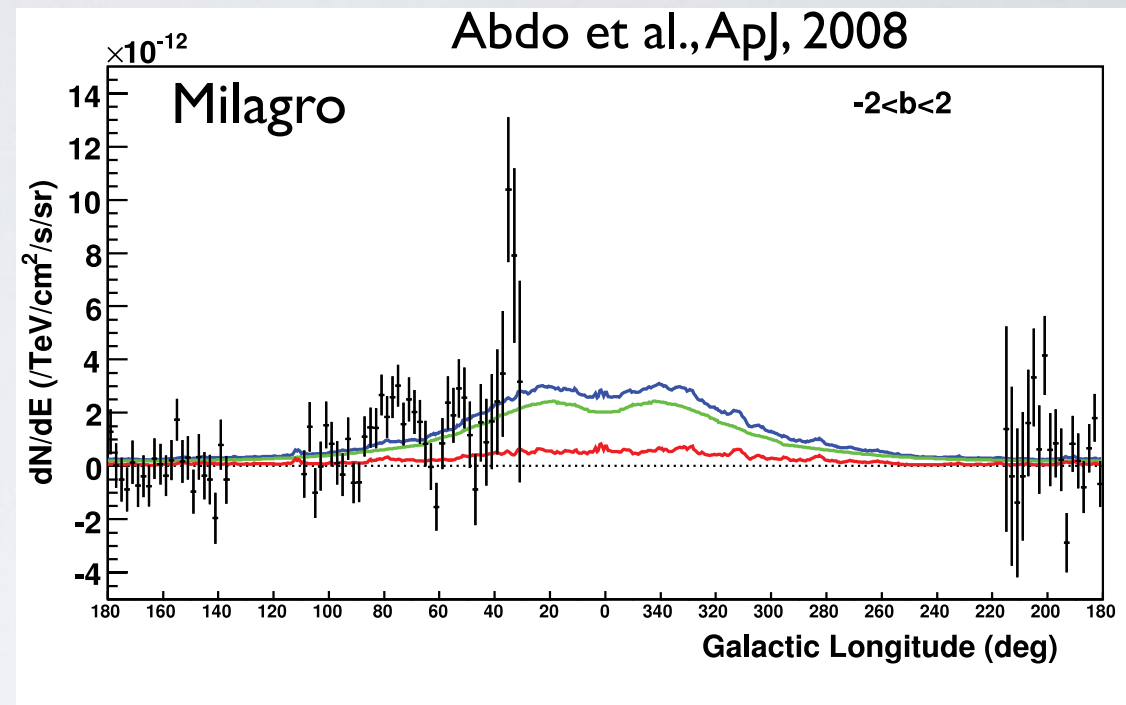
- 2HWC J2031+415 — TeV J2032+4130, a PWN
- 2HWC J2020+403 — VER J2019+407, UID encompassing SNR G78.2+2.1 and PSR J2021+4026
- extended emission region 2HWC J2025+410\* and 2HWC J2027+403\* at Fermi cocoon / ARGO superbubble region



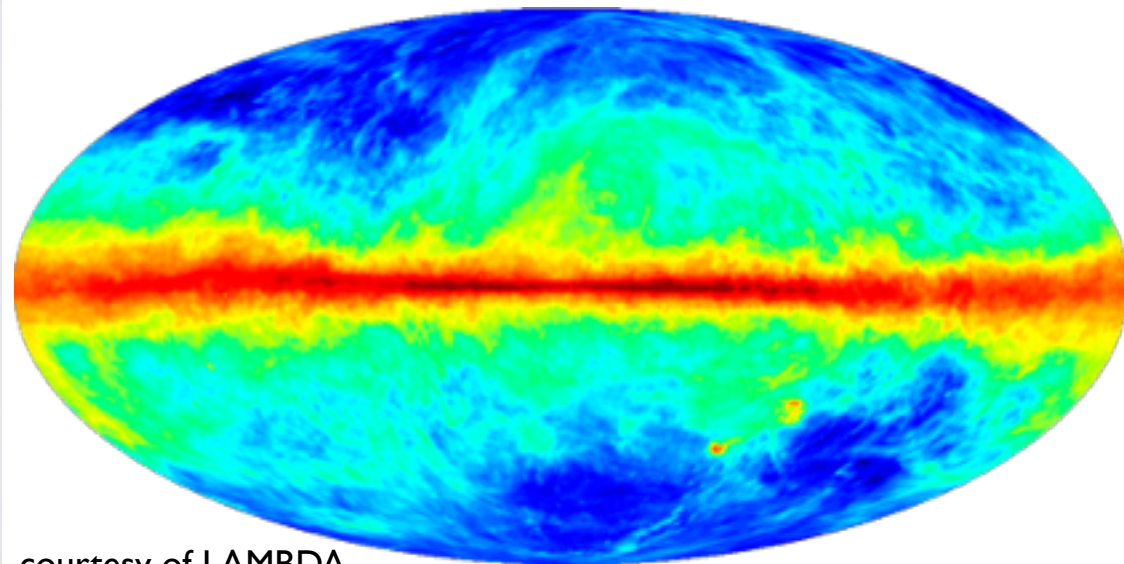
# Galactic Diffuse Emission

Diffuse contributions:

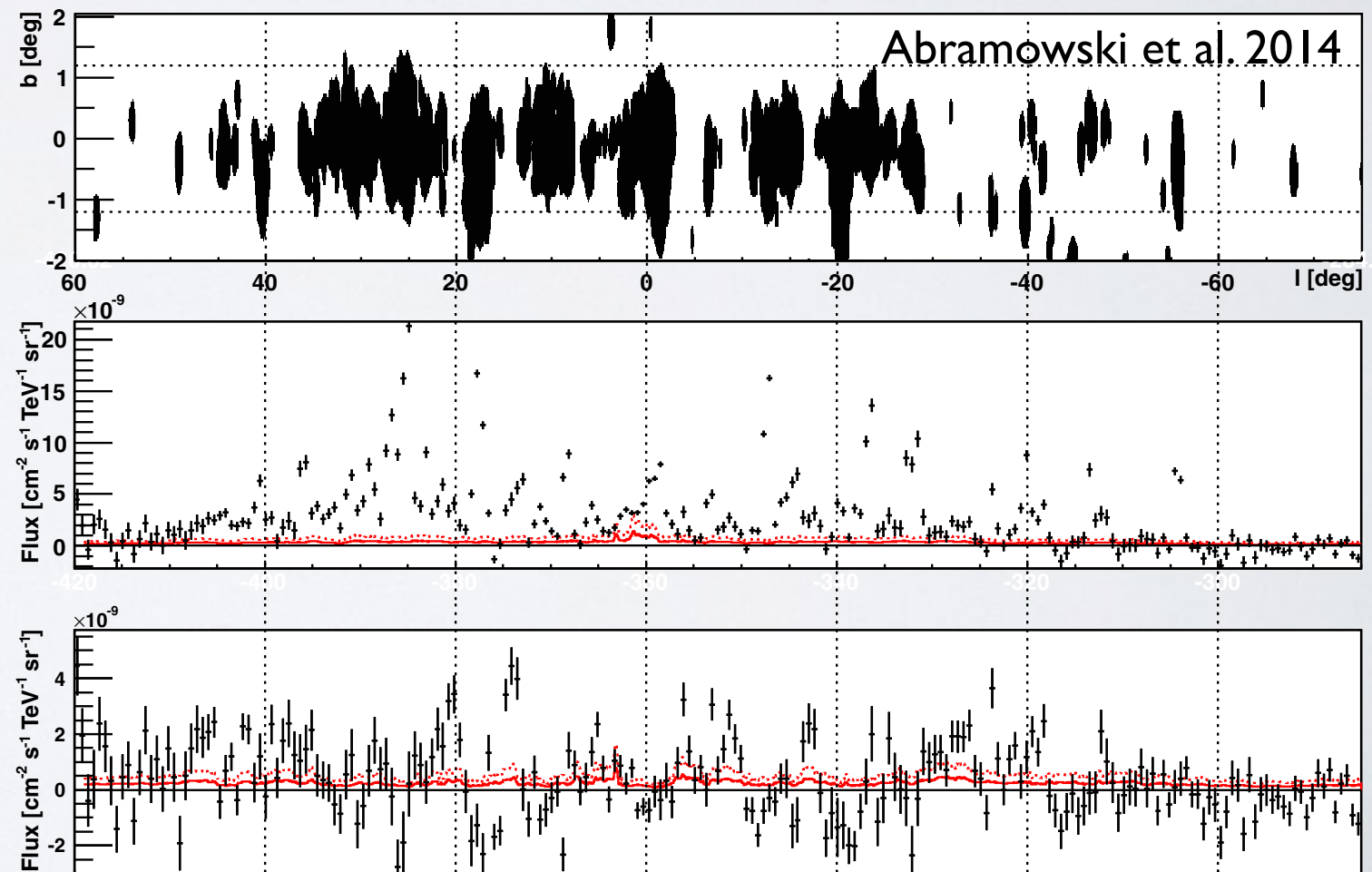
- Cosmic-ray interactions
  - molecular clouds
  - interstellar gas
- Inverse Compton
- Unresolved sources.



Leiden/Argentine/Bonn (LAB) Survey of Galactic HI

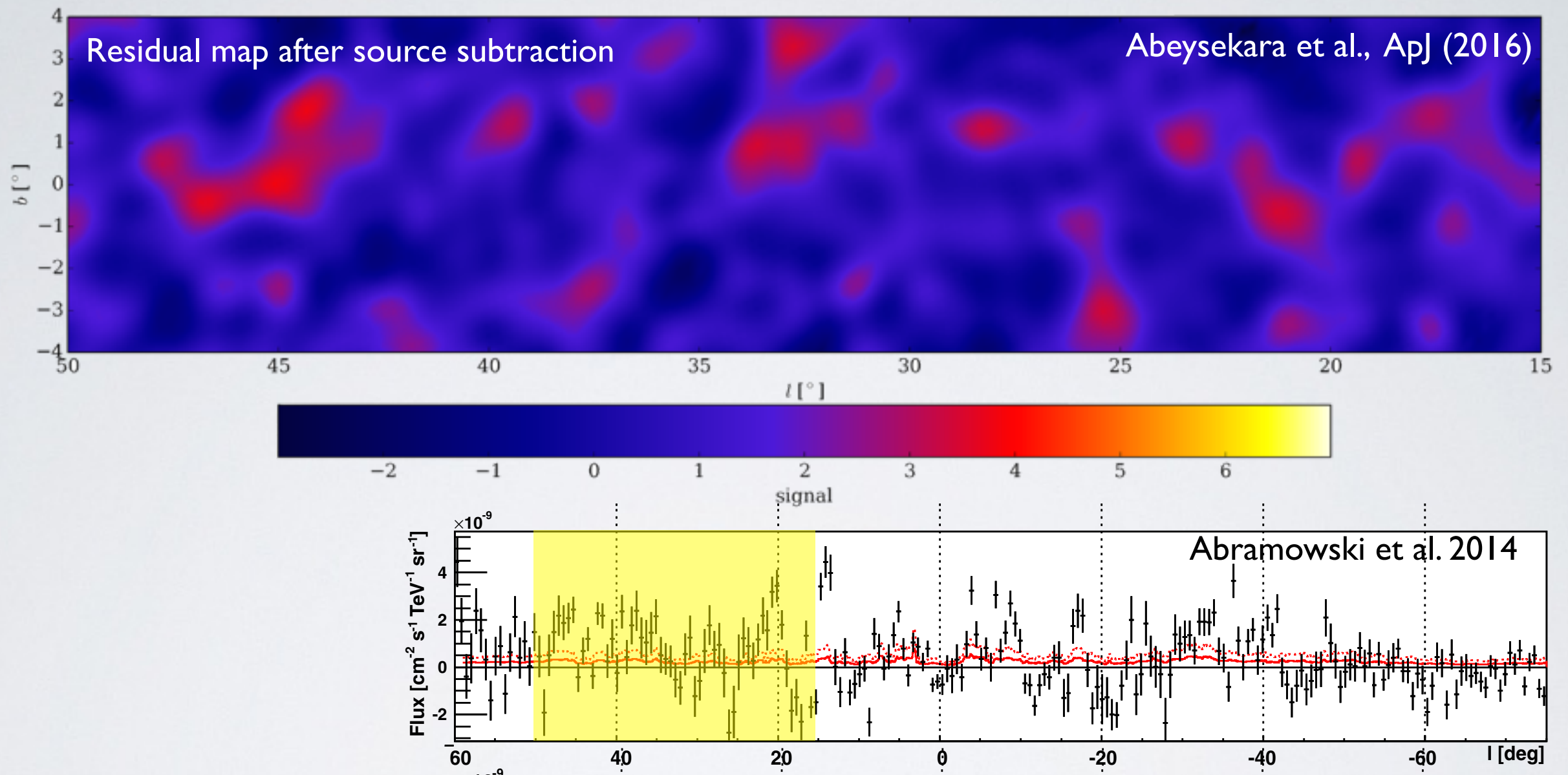


courtesy of LAMBDA





# Galactic Diffuse — Limit from Pass I

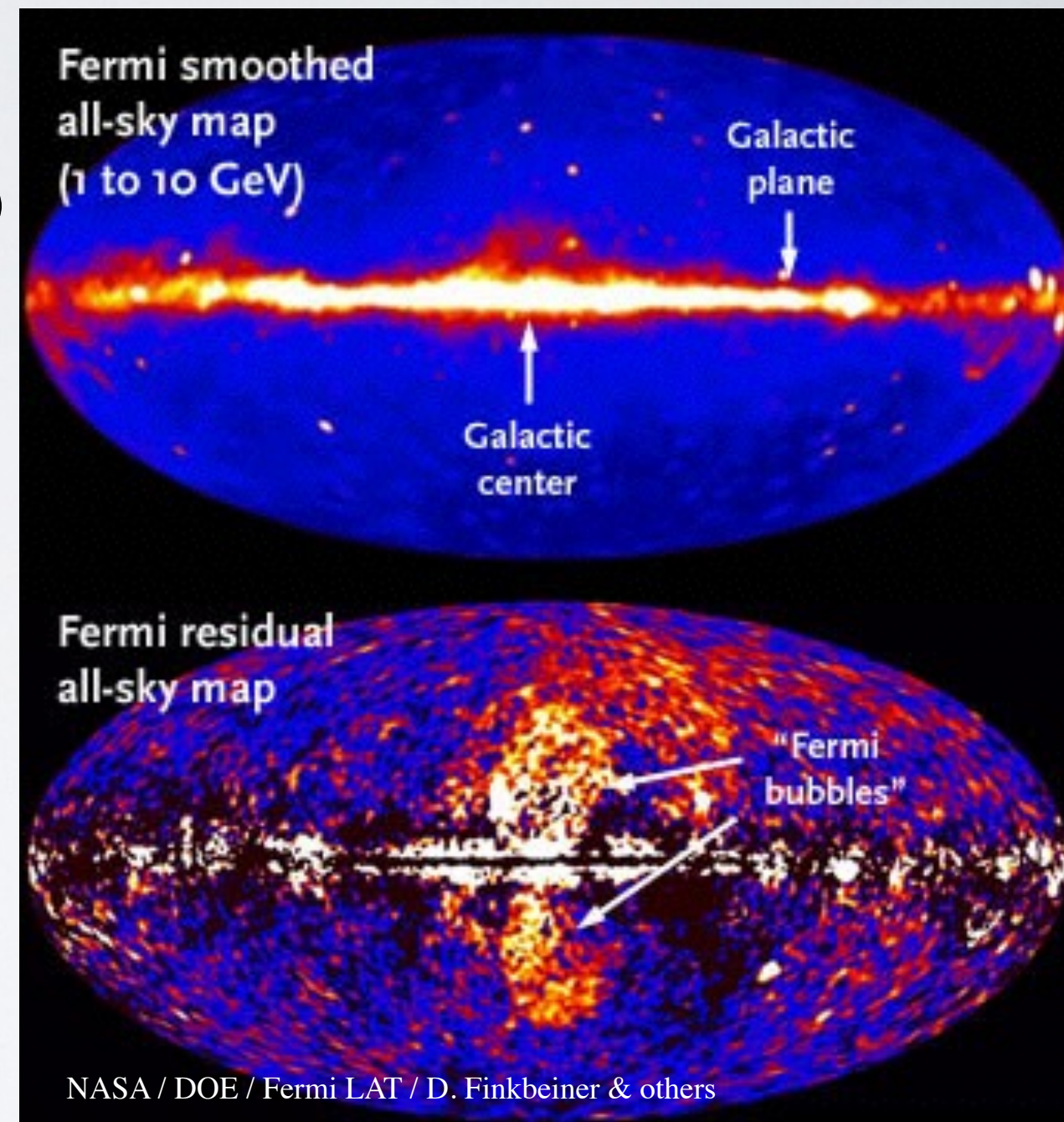
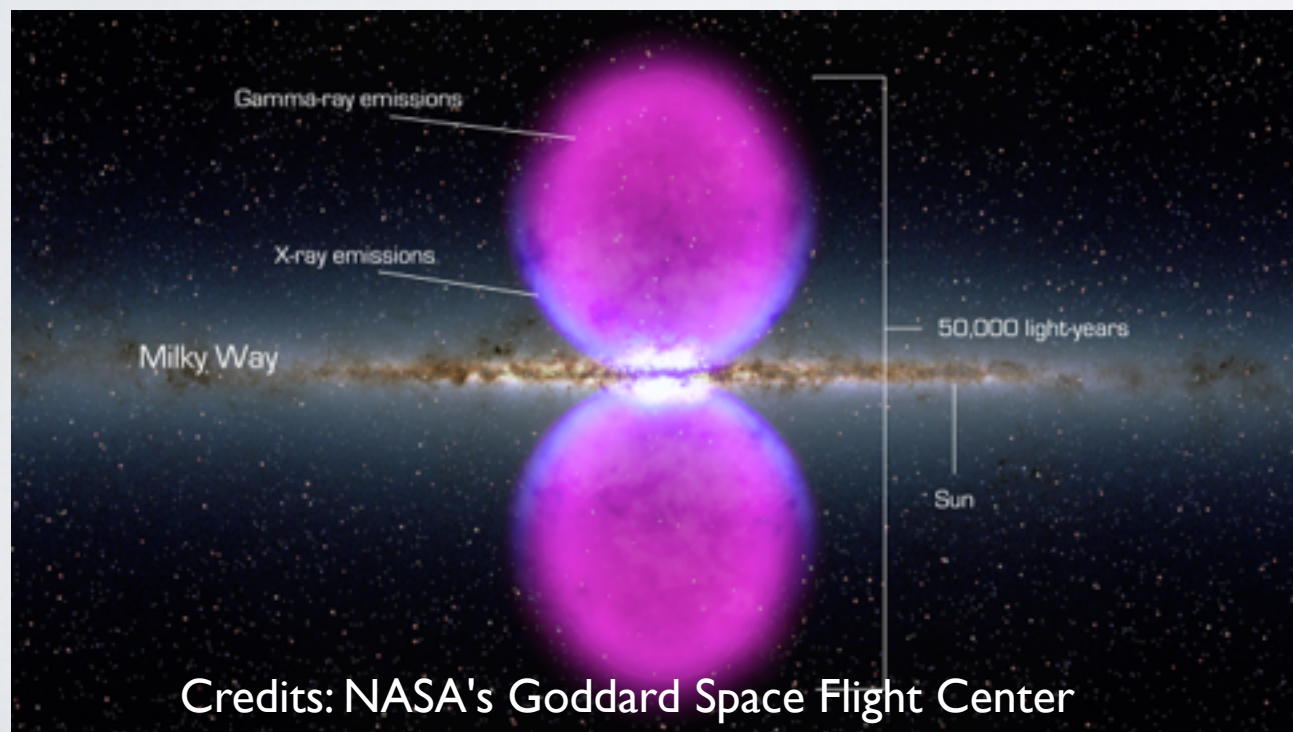


- A uniform surface brightness fit in addition to source model is preferred at  $5.7\sigma$ .
- The fitted surface brightness at 5 TeV is  $1.6 \pm 0.4 \times 10^{-11} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ .
- HESS average diffuse extrapolated to 5 TeV is  $1.0 \pm 0.2 \times 10^{-11} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ .
- Current limit from HAWC-III dataset includes unresolved sources.



# Large-scale structures e.g. Fermi Bubbles

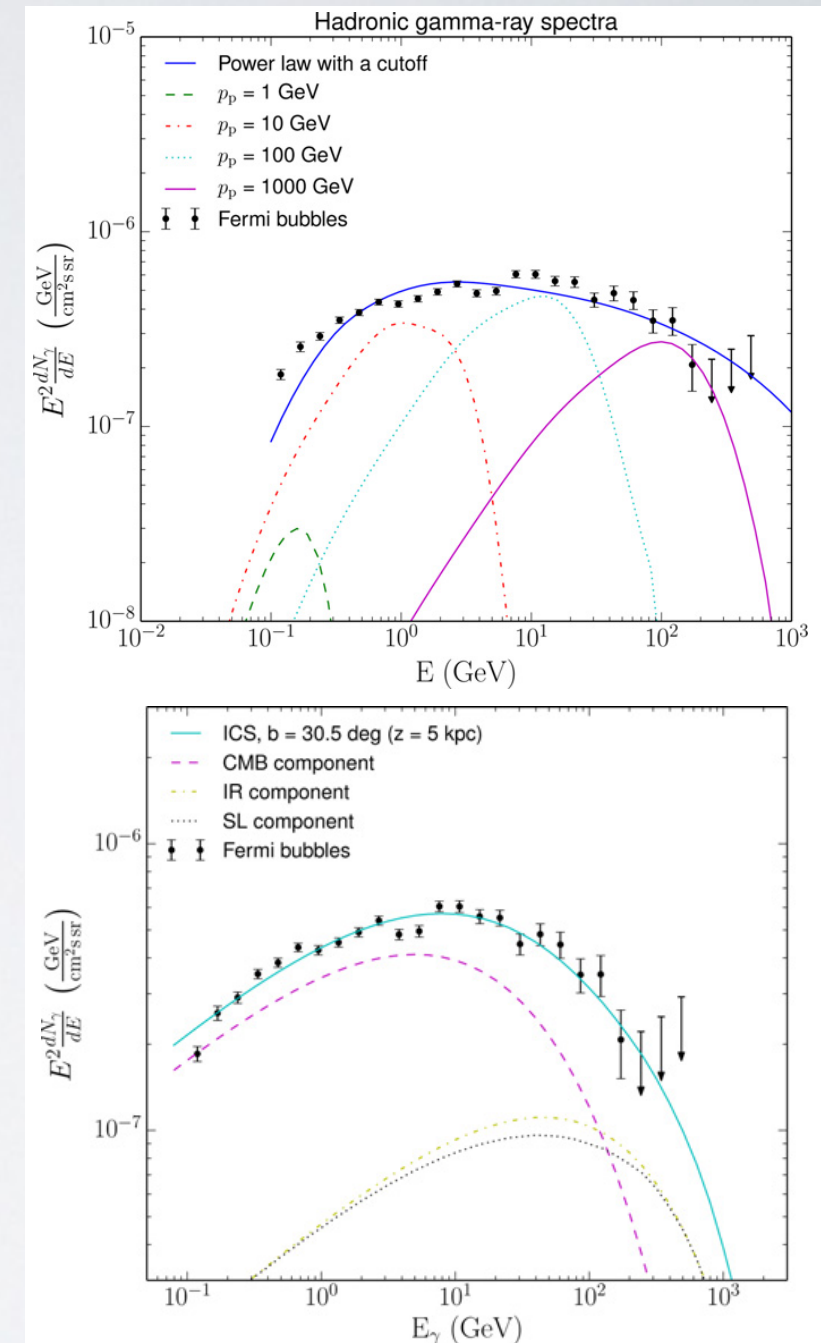
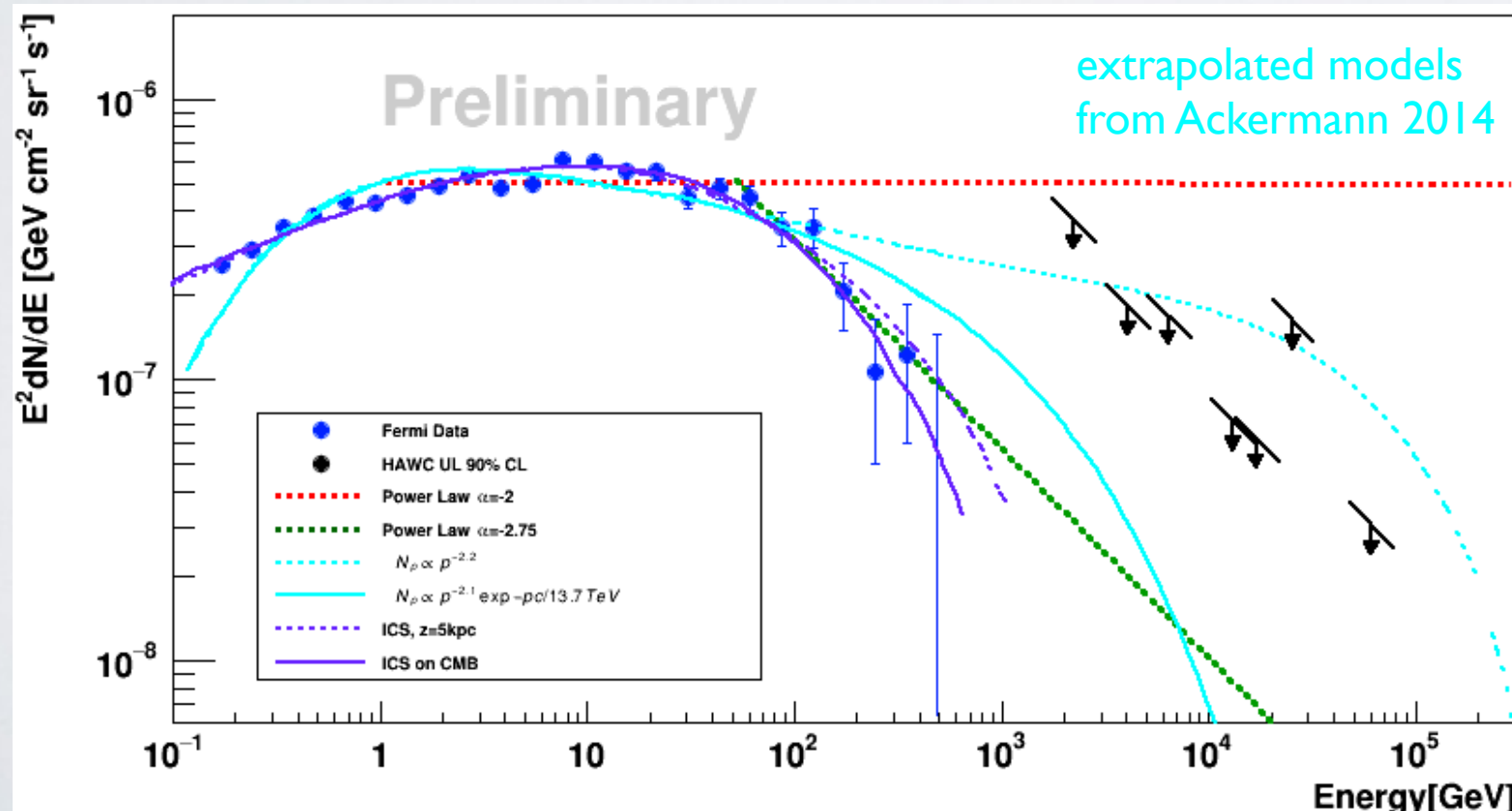
- Large scale, non-uniform structures extending above and below the Galactic center.
- Edges line up with X-ray features.
- Correlate with microwave excess (WMAP haze)
- Both hadronic and leptonic model fit Fermi LAT data. Leptonic model can explain both gamma ray and microwave excess.





# Large-scale structures e.g. Fermi Bubbles

- Large scale, non-uniform structures extending above and below the Galactic center.
- Edges line up with X-ray features.
- Correlate with microwave excess (WMAP haze)
- Both hadronic and leptonic model fit Fermi LAT data. Leptonic model can explain both gamma ray and microwave excess.
- First limits in TeV, hard spectrum is highly unlikely.



Ackermann et al. ApJ (2014)



# Transient Search

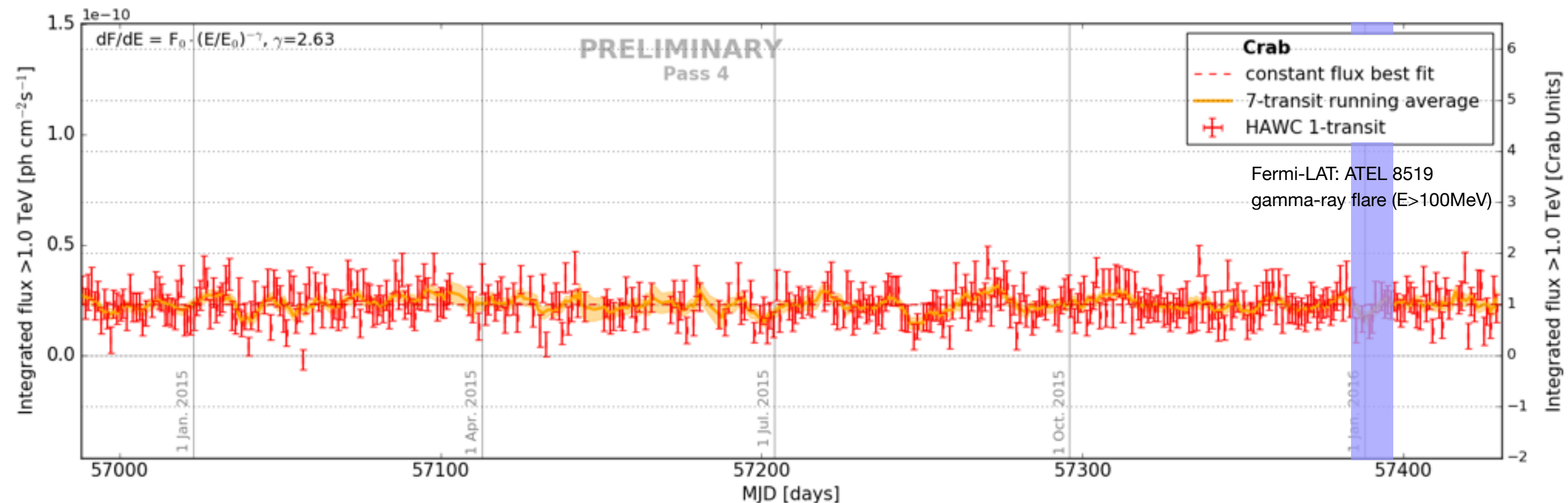
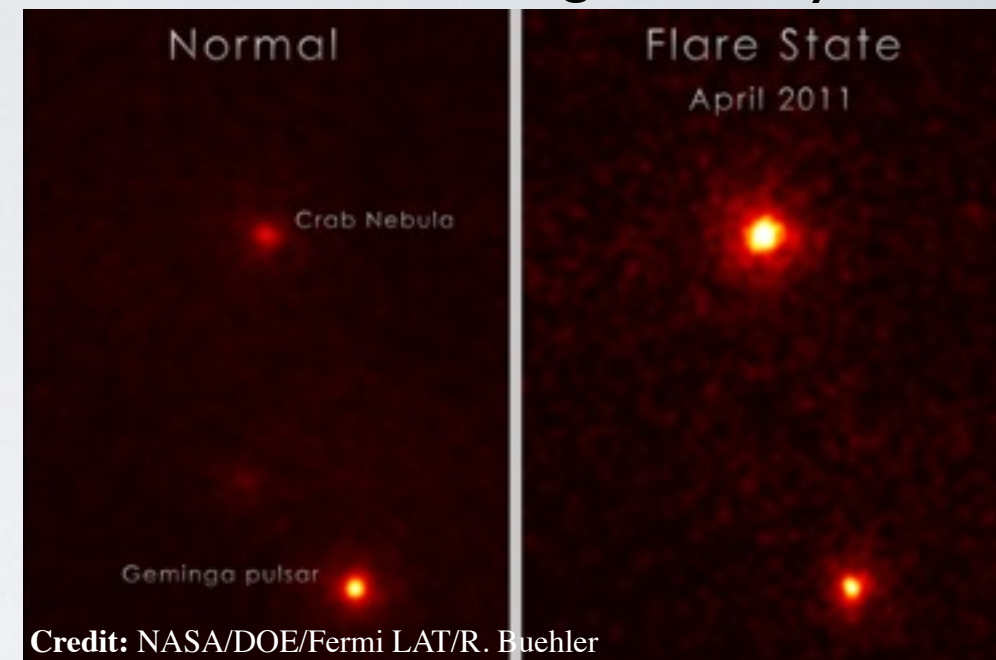
## Crab Nebula

- Crab flares, continue up to TeV?
- No activity in radio, IR, and X-rays.

HAWC observation:

- Data is consistent with a constant flux.
- Coincident observation with Fermi-LAT reported Crab flare starting Jan 7 2016.
- 95% C.L. upper limit on 13-day average flux above 1 TeV is 1.01x average Crab flux.

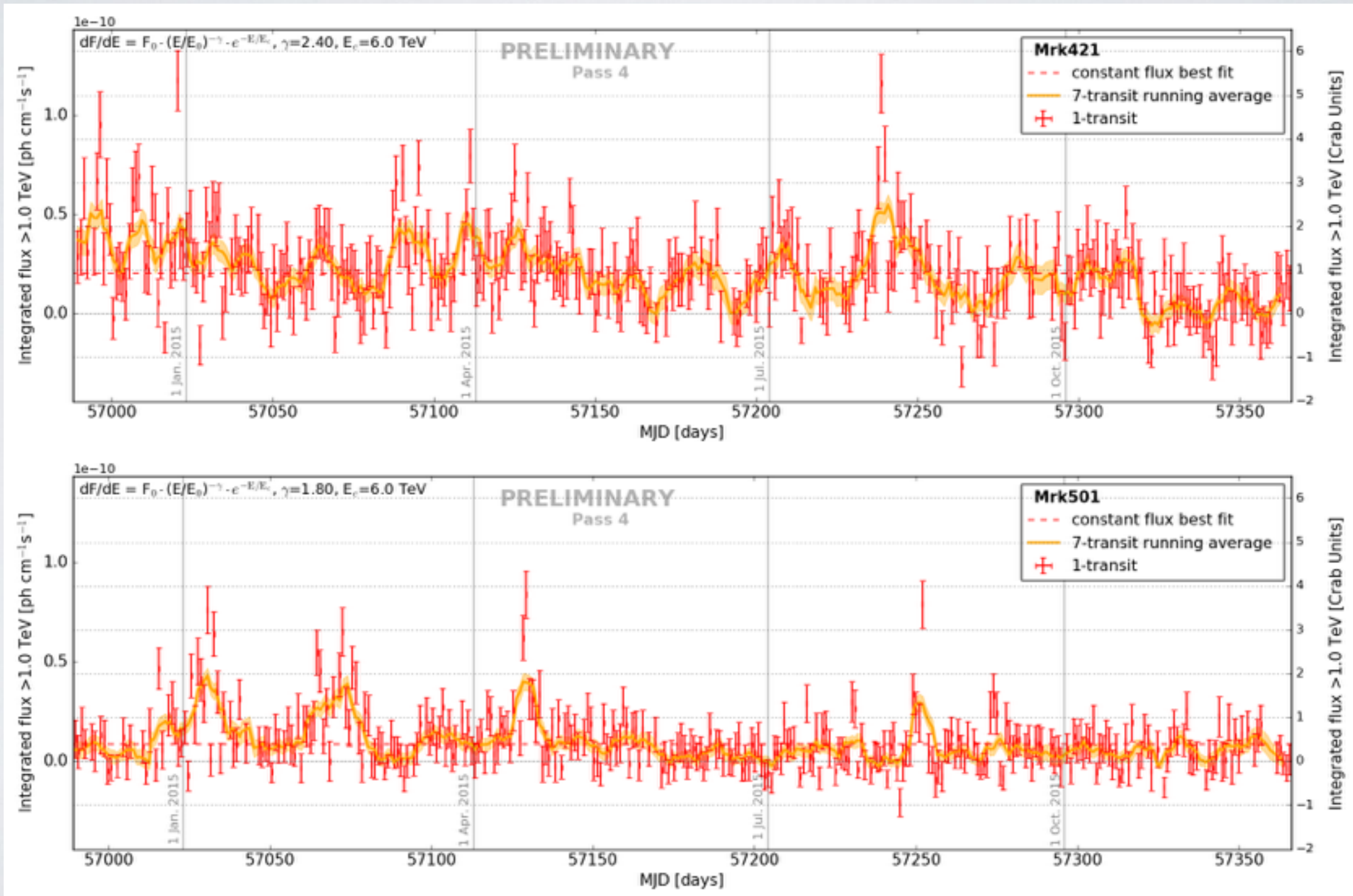
MeV-GeV gamma ray





# Transient Search

## AGN flares Mrk 421 / Mrk 501





# Multi-wavelength / Multi-messenger

Have follow-up agreement with:

- Swift
- Fermi-LAT
- IACTs
  - FACT
  - HESS
  - MAGIC
  - VERITAS
- AMON
- IceCube
- ANTARES
- LIGO/VIRGO

HAWC-triggered:

- New source candidates lists.
  - follow-up observations by IACTs such as VERITAS and MAGIC from Pass I release.
- Flares from known gamma-ray sources.

HAWC ATel #8922  
on Mrk 501 flare

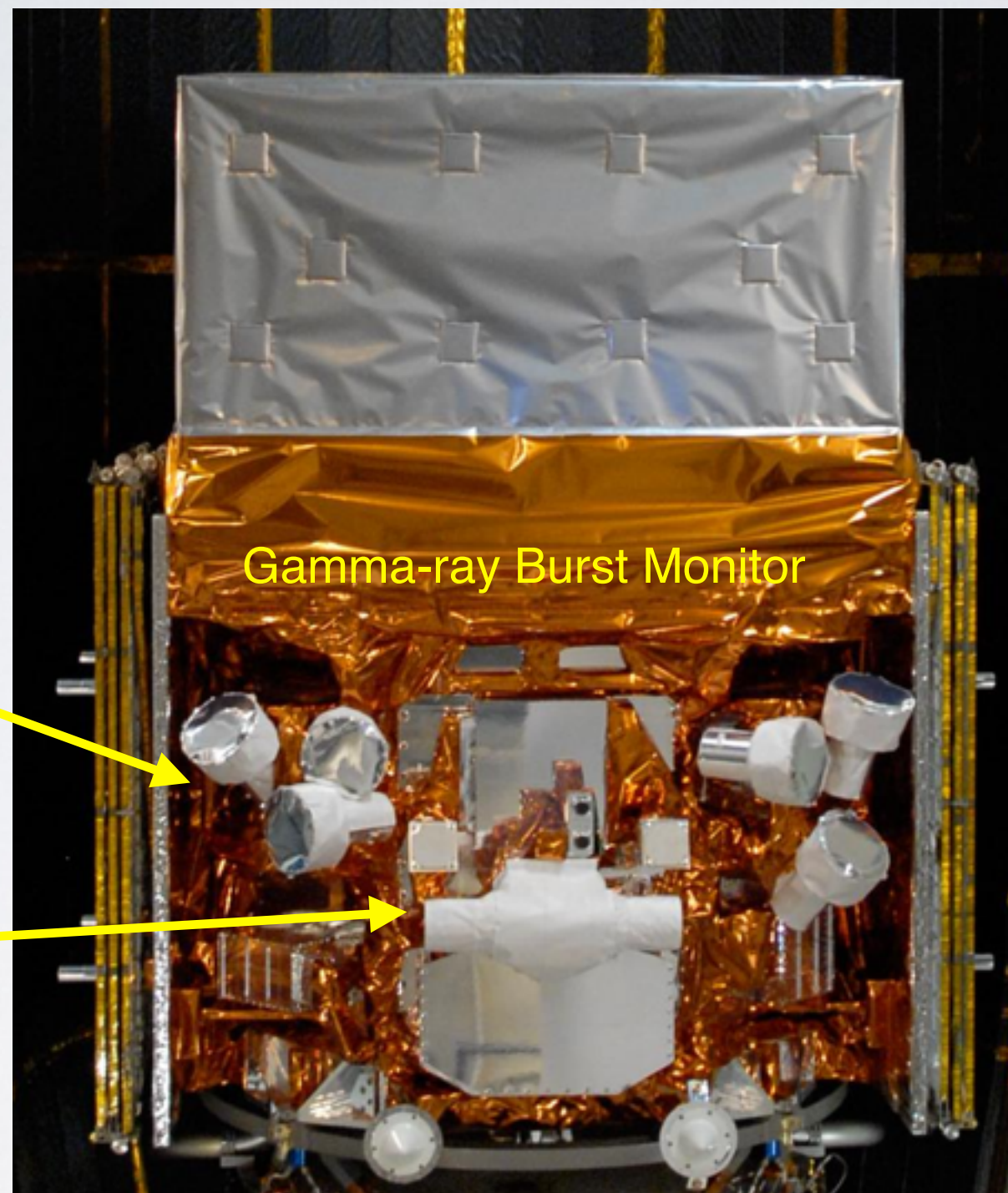
Externally triggered:

- IceCube alert on high confidence neutrino event (highest energy pointed astrophysical track-like).
- Fermi alerts on flaring activities.
- LIGO/VIRGO gravitational wave event follow-up

IceCube ATel: #7856  
HAWC Follow-up  
ATel: #7868



# Fermi Gamma-ray Space Telescope



12 NaI detectors  
(8keV—1MeV)

2 BGO detectors  
(200keV—40MeV)

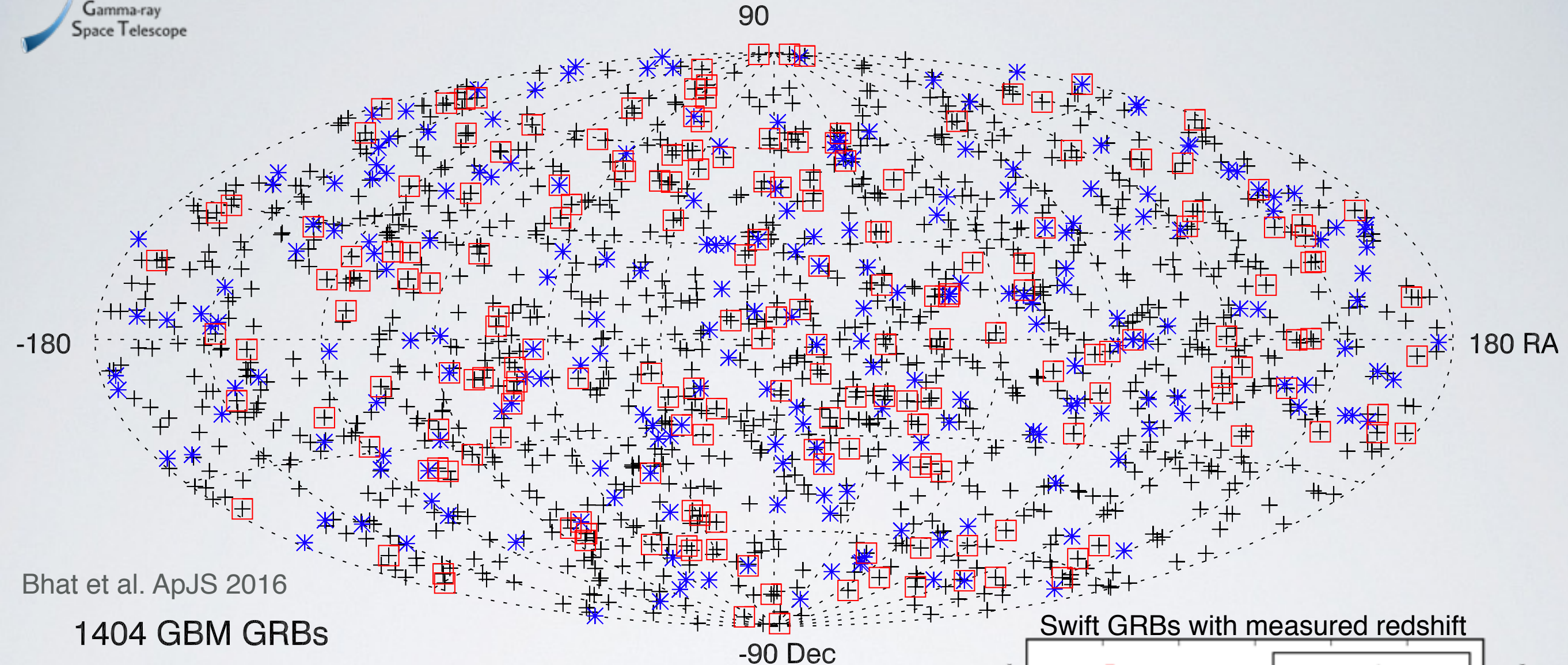
Gamma-ray Burst Monitor

GBM:

- FOV  $>8\text{sr}$
- Whole sky every  $\sim 90\text{min}$



# Fermi GBM GRBs in first six years of operation



Bhat et al. ApJS 2016

1404 GBM GRBs

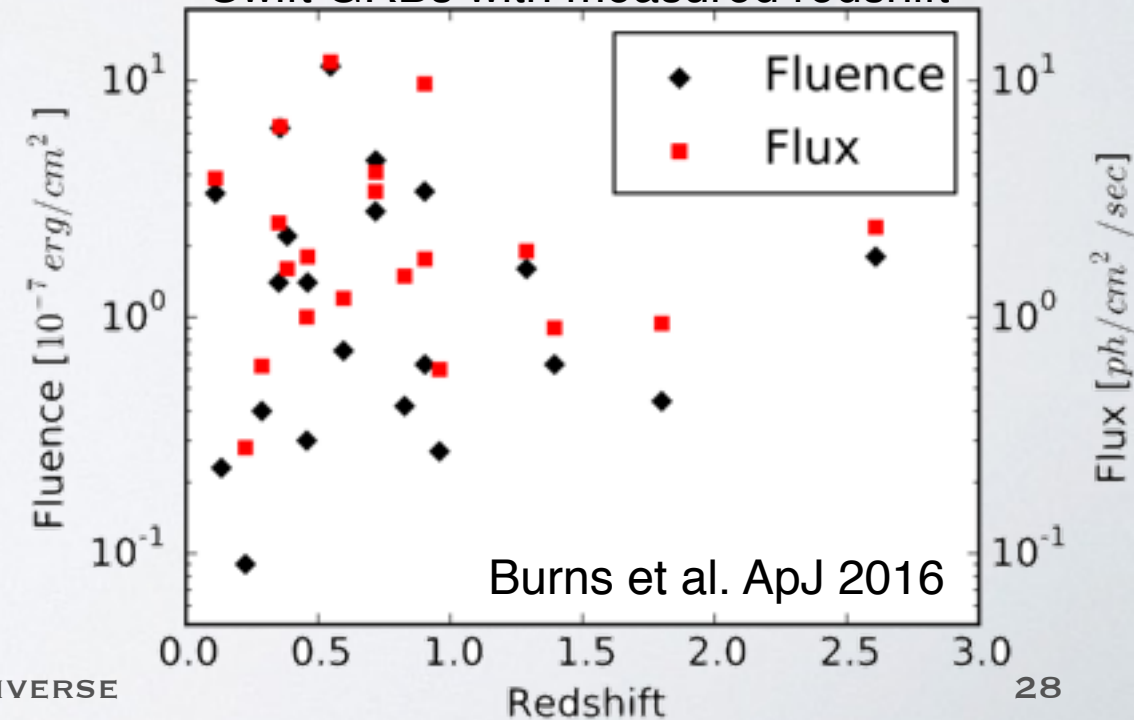
+ 1175 Long

\* 229 Short

□ 191 also triggered Swift-BAT

- Brightness of weak short GRBs does not appear to be redshift dependent
  - i.e. weak  $\neq$  far away

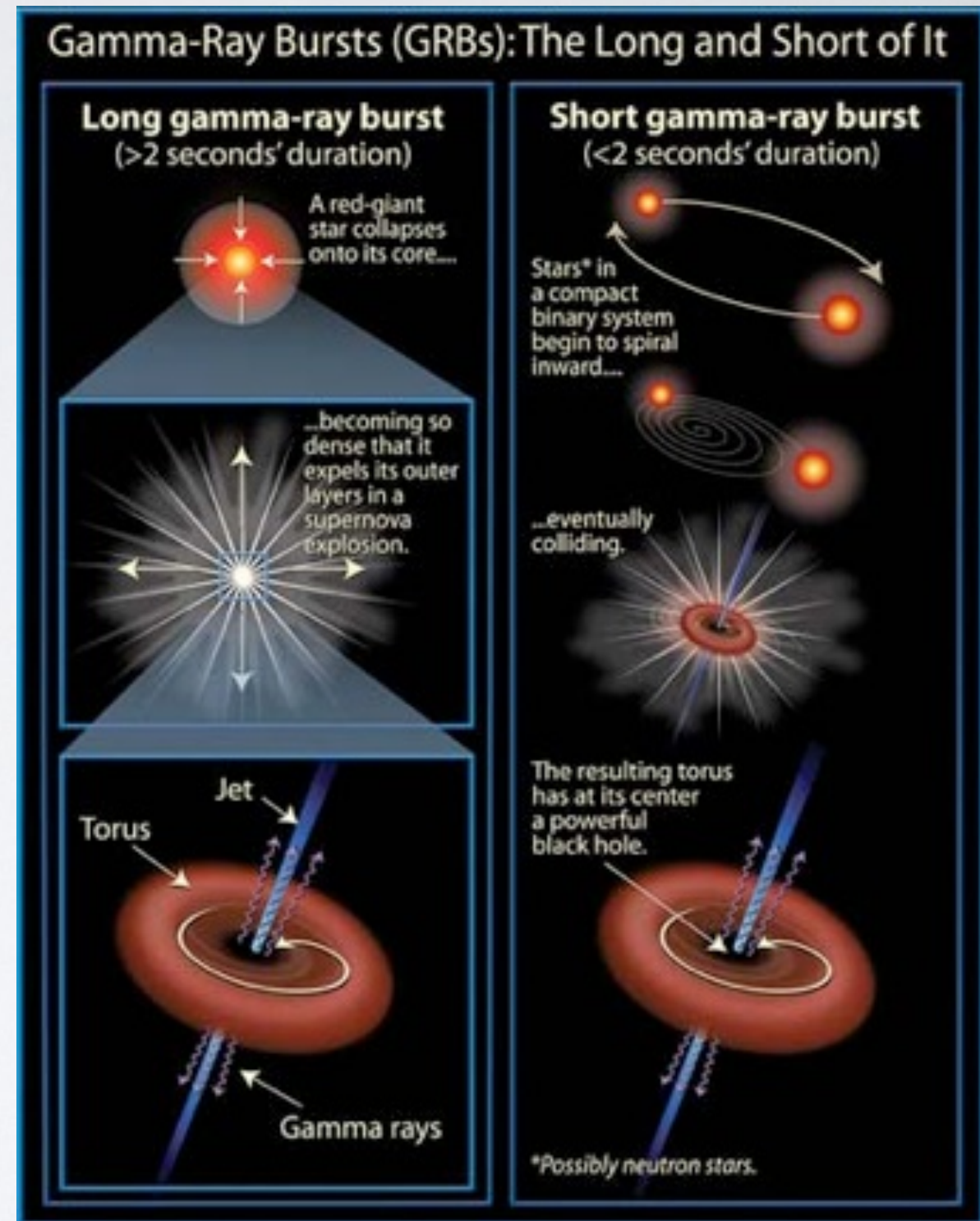
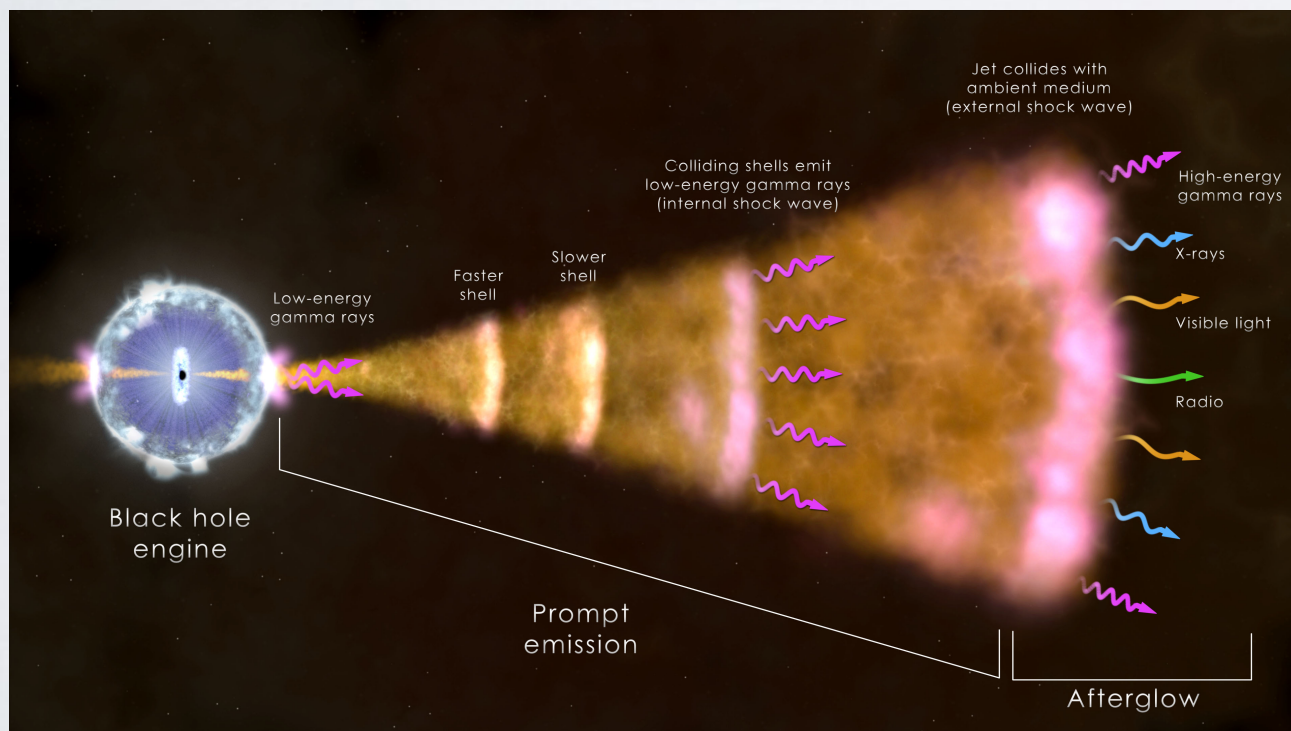
Swift GRBs with measured redshift





# Gamma-ray Bursts

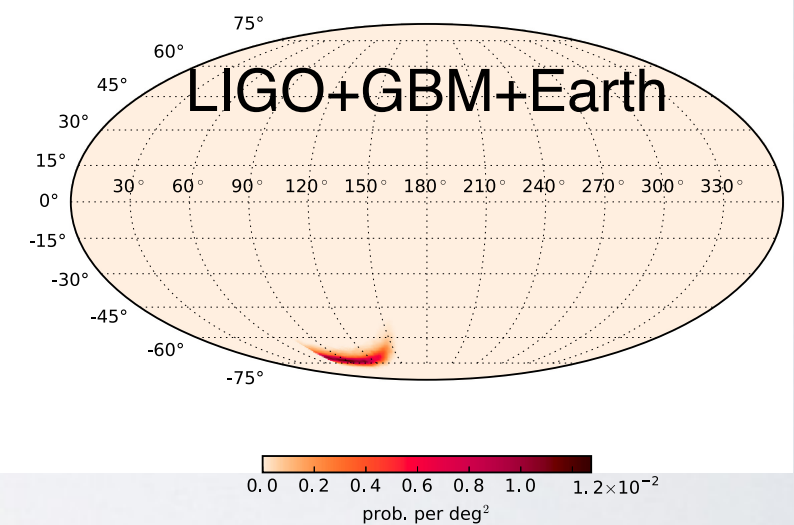
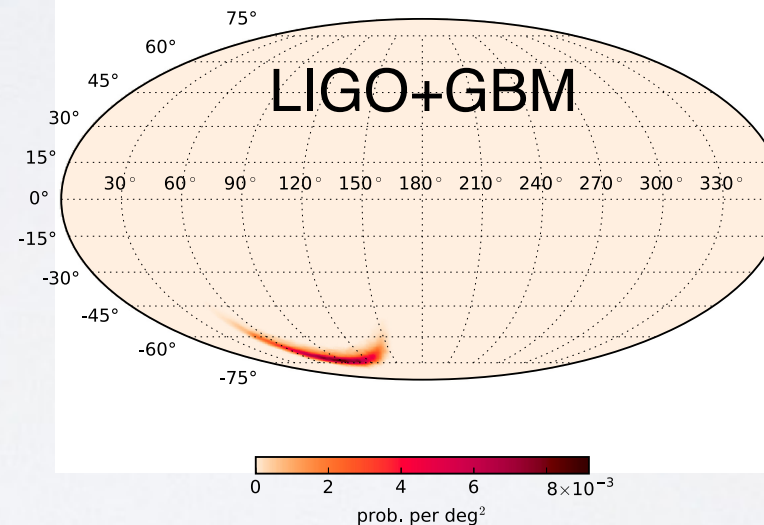
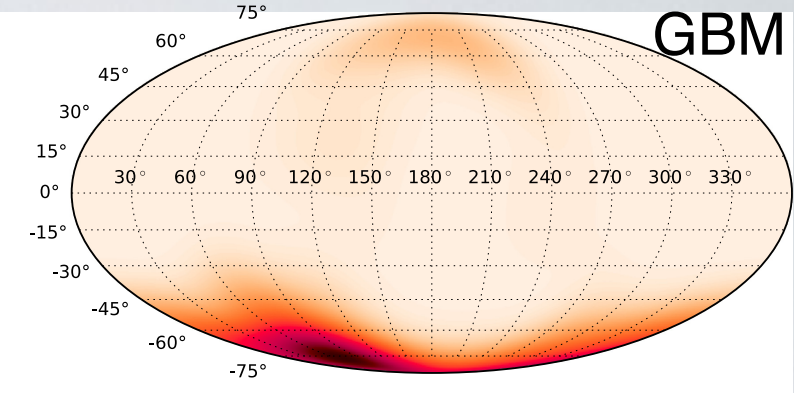
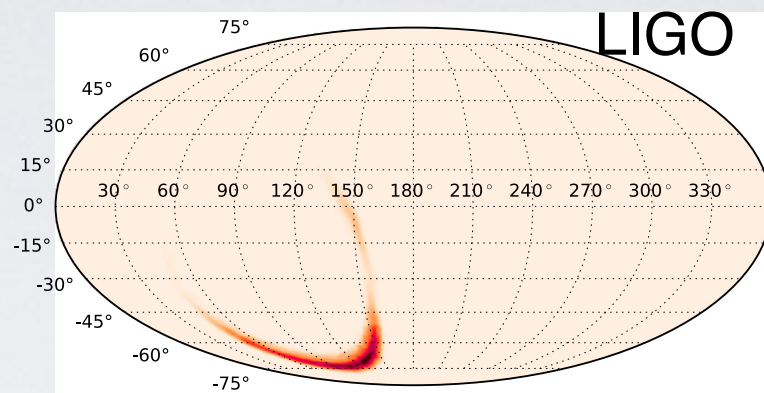
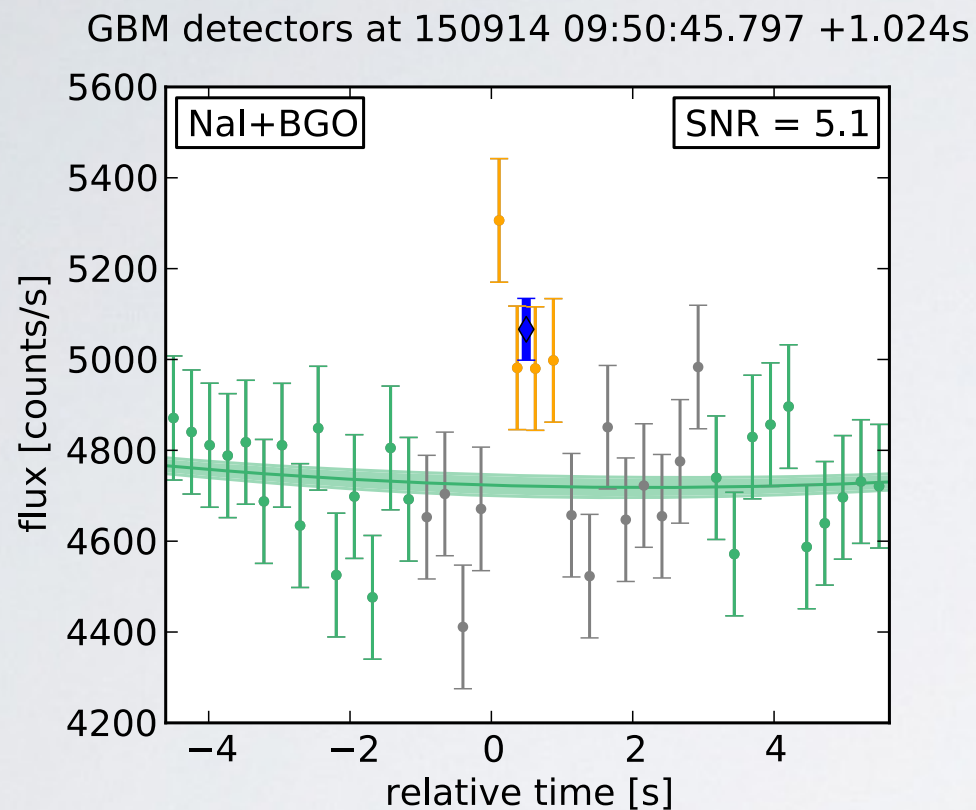
- Collapse of a massive star or merger of two compact objects.
- Collimated relativistic outflow.
- Prompt keV-MeV emission, afterglow in other wavelengths.
- Detected  $\sim$  once per day, distributed all over the sky.





# Follow-up to Gravitational Wave Event GW150914

Connaughton et al. ApJL 2016



601 sq deg → 199 sq deg

- Untriggered sub-threshold signal 0.4s after LIGO trigger.
- Consistent with a low-fluence short GRB coming from behind Fermi.
- Poorly localized but consistent with LIGO localization.
- 0.2% post-trials probability in statistical fluctuation.



# Untriggered GBM GRB search

- In addition to the directed search with LIGO events, untriggered search in the Continuous Time Tagged Events (CTTE) data is ongoing.
  - 2  $\mu$ s time resolution with 128 energy channels
  - 10+ timescales: 64ms to 2.8+ s
  - multiple energy ranges
- Working towards creating automated GCNs, will be distinct from triggered events type.

[http://gammaray.nsstc.nasa.gov/gbm/science/sgrb\\_search.html](http://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html)

Short GRB Candidates							
MET	RANK	DATE (UT)	TIME (UT)	RA (DEG)	DEC (DEG)	ERROR (DEG)	COMMENT
<a href="#">423745096.625</a>	1.91E-0016	2014-06-06	10:58:13.625	232.07	+37.47	18.86	
<a href="#">424708158.025</a>	2.36E-0007	2014-06-17	14:29:15.025	359.06	-32.47	5.59	
<a href="#">424757010.500</a>	1.92E-0016	2014-06-18	04:03:27.500	278.84	+64.38	4.67	
<a href="#">424968038.500</a>	2.80E-0007	2014-06-20	14:40:35.500	319.45	-17.40	17.05	
<a href="#">426319641.550</a>	2.00E-0010	2014-07-06	06:07:18.550	64.10	+25.04	6.41	
<a href="#">426588599.600</a>	7.75E-0014	2014-07-09	08:49:56.600	12.77	-49.36	6.53	
<a href="#">426950830.700</a>	4.21E-0007	2014-07-13	13:27:7.700	264.57	-87.36	13.49	
<a href="#">427440502.000</a>	2.65E-0007	2014-07-19	05:28:19.000	34.37	+45.94	15.21	
<a href="#">431283951.000</a>	3.82E-0008	2014-09-01	17:05:48.000	80.94	+69.19	16.02	
<a href="#">431291510.000</a>	3.03E-0007	2014-09-01	19:11:47.000	81.08	-17.32	15.88	
<a href="#">432797599.000</a>	3.30E-0007	2014-09-19	05:33:16.000	177.15	-37.38	20.86	
<a href="#">433789586.000</a>	1.95E-0007	2014-09-30	17:06:23.000	283.03	-9.27	11.33	

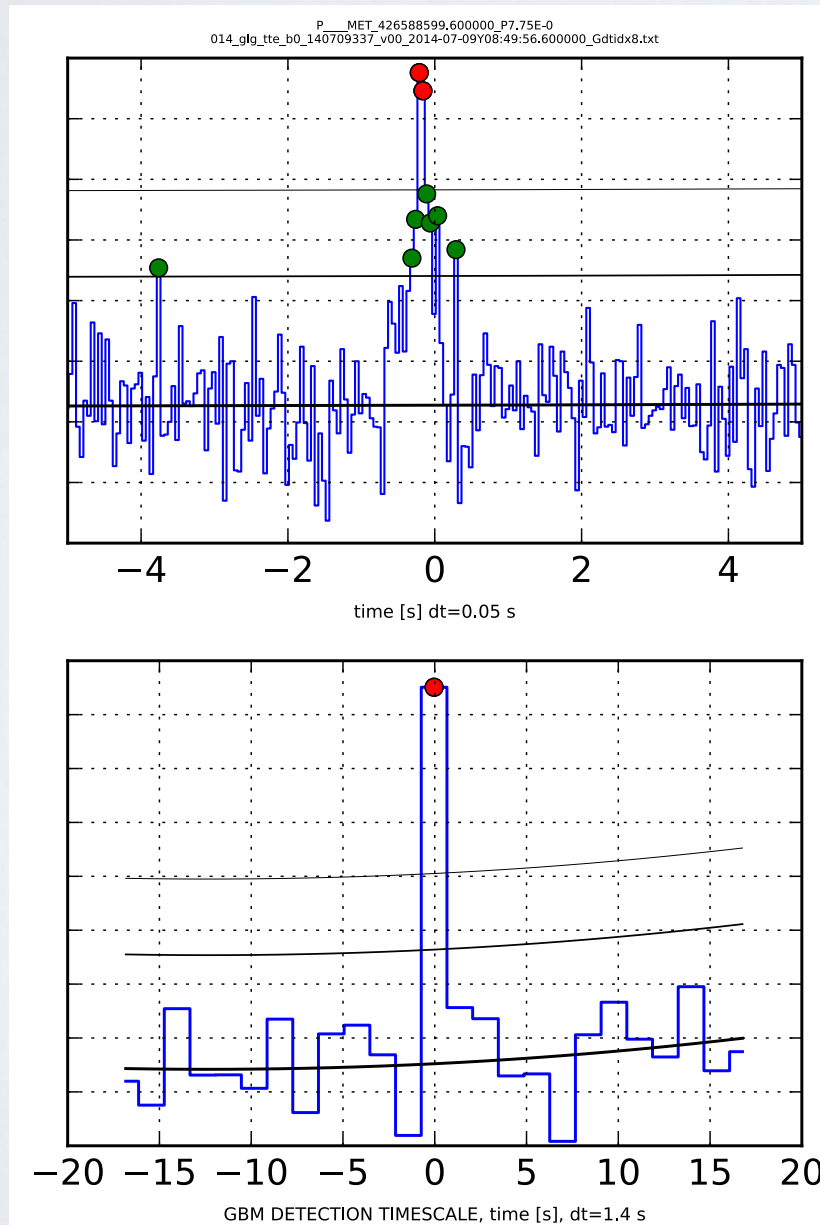


# GBM Candidate Event

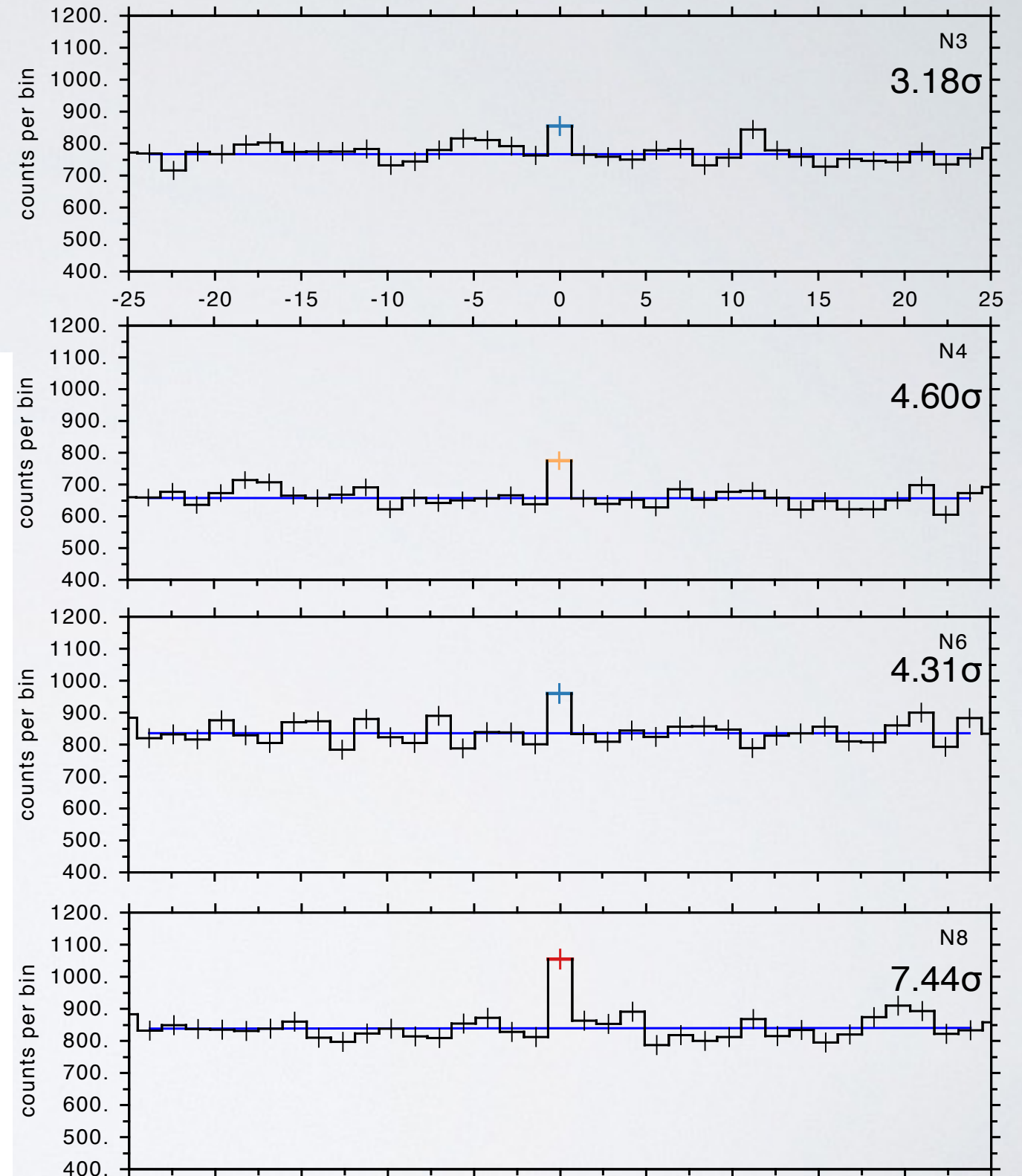
- 2014-07-09 08:49:56.600
- Found in 1.40s time binning
- 25 - 494 keV energy range
- $P=7.75e-14$

INTEGRAL Anti-Coincidence Shield(ACS) lightcurve

ACS native  
time bin



GBM timescale



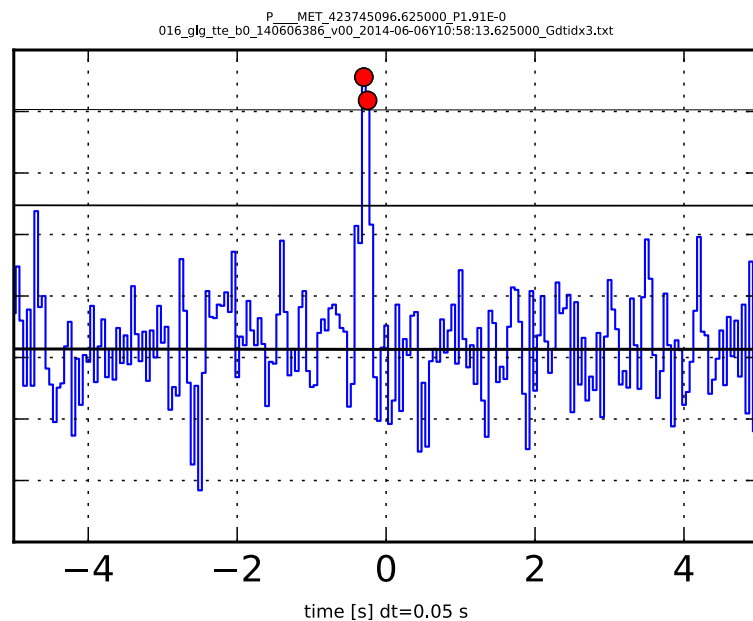


# GBM Candidate Event

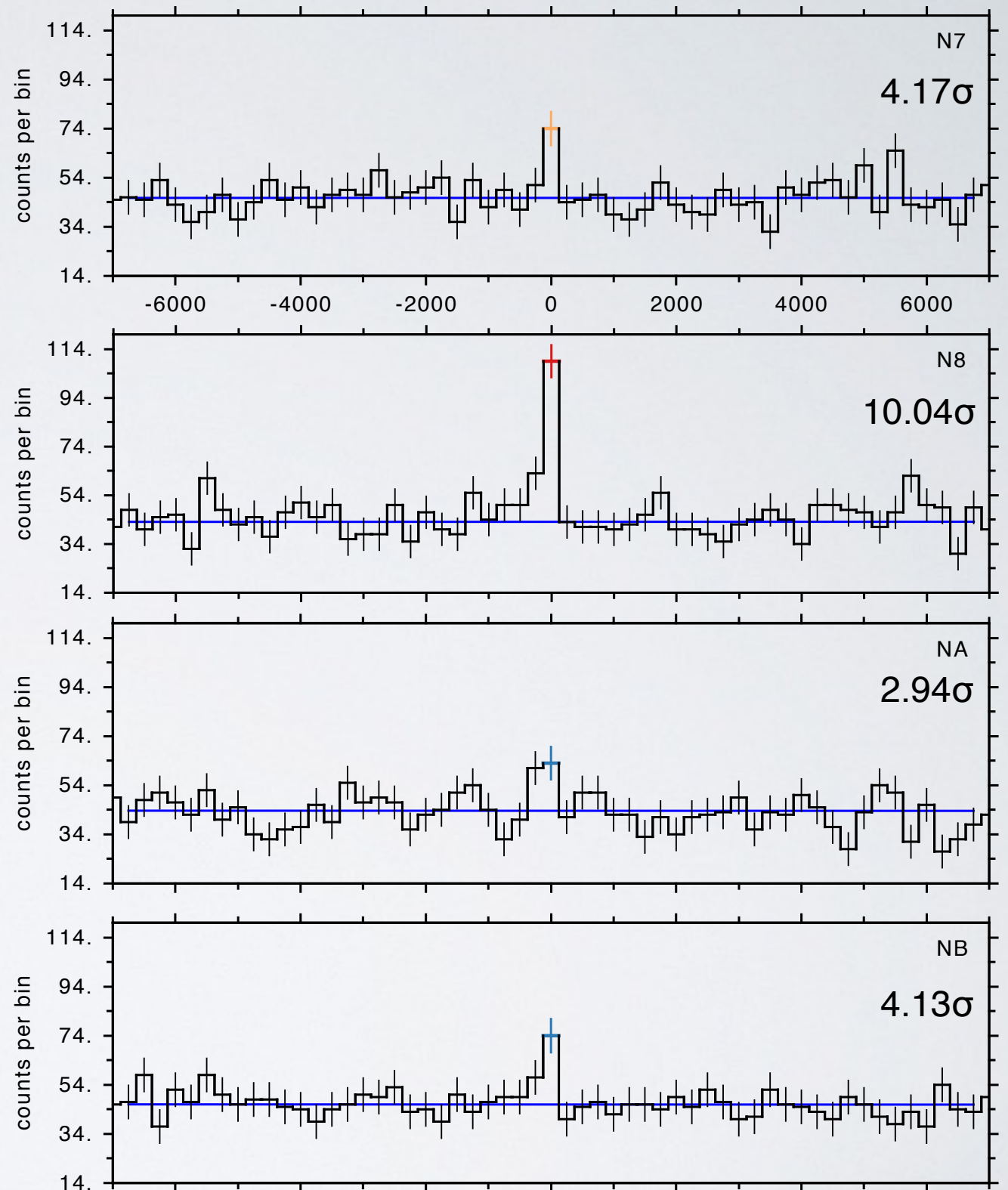
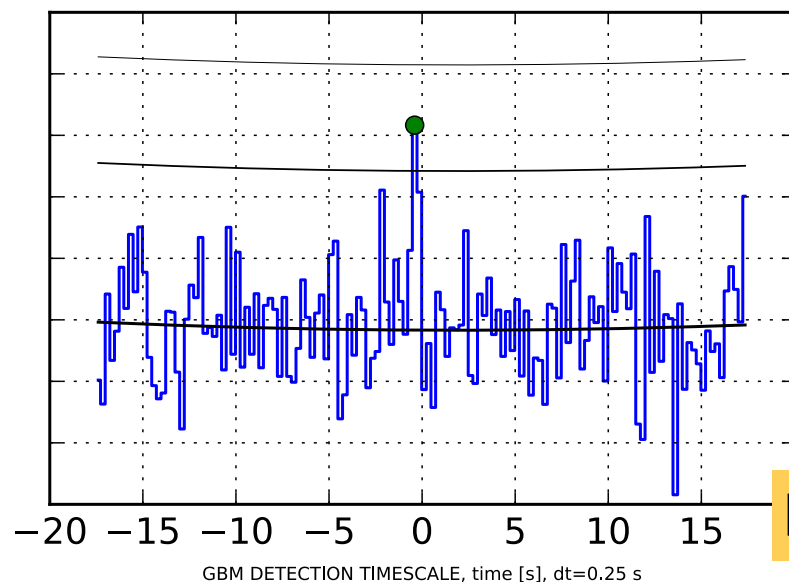
- 2014-06-06 10:58:13.625
- **Swift GRB 140606A**
- Found in 0.25s time binning
- 93 - 494 keV energy range
- $P=1.91\text{e-}16$

INTEGRAL ACS lightcurve

ACS native  
time bin



GBM timescale



Not all GBM triggered short GRB are detected by ACS.



# Outlook

- Both Fermi and HAWC surveying and monitoring the gamma-ray sky in different energies, with ground-based telescopes such as VERITAS ready for follow-up.
- Many instruments from different waveband/messenger (X-rays, neutrinos, gravitational waves) available for simultaneous observation.

- HAWC observatory catalog of first year full operation is in prep (2HWC), with new TeV sources!
- Diverse science results, stay tuned!
- Upgrade to expand the array to enhance effective area  $>10$  TeV by 3-4x is currently under installation.